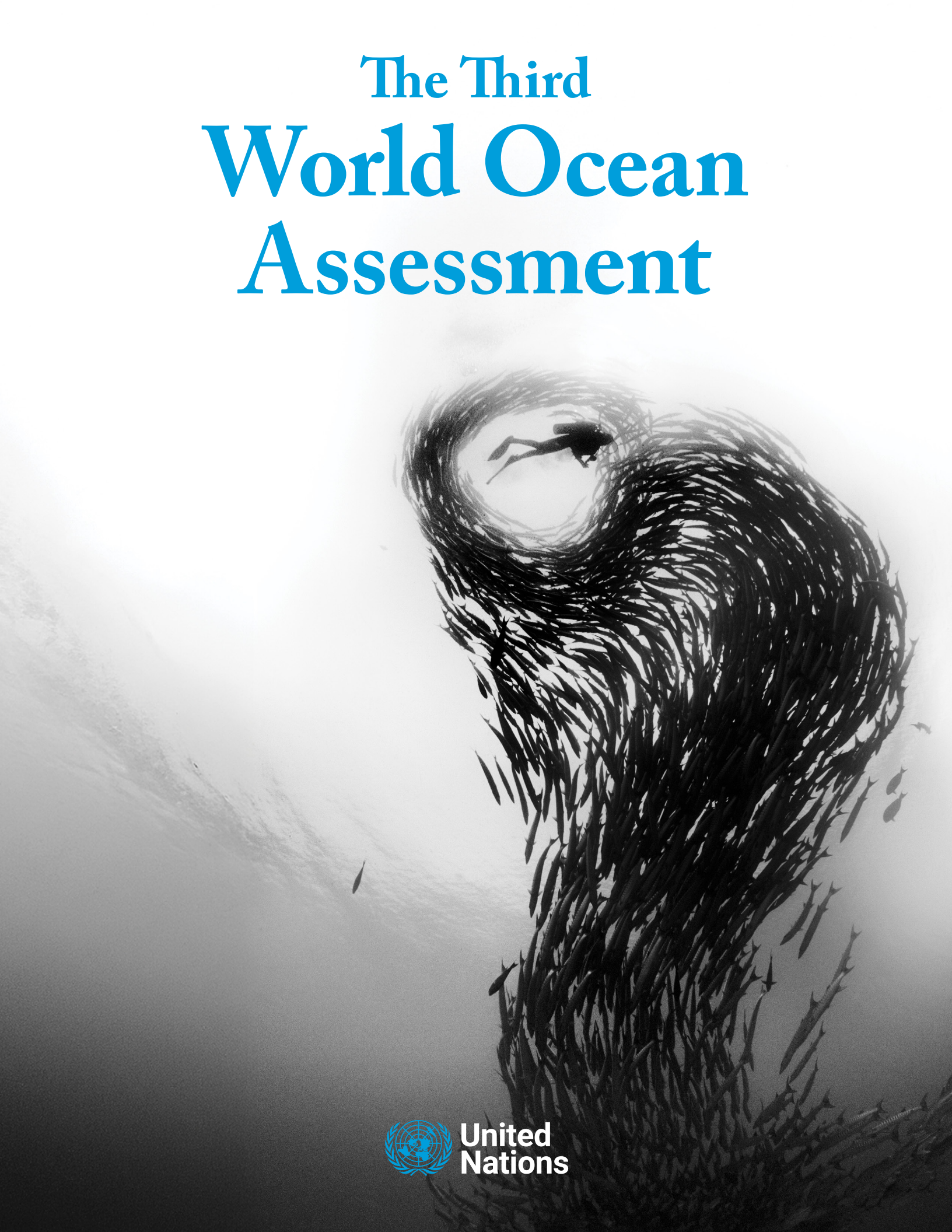
The Third World Ocean Assessment



United Nations

The Third World Ocean Assessment

WORLD OCEAN ASSESSMENT III

United Nations

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Foreword for the third *World Ocean Assessment*

The ocean is the foundation of life on Earth. But its health is at grave risk as ecosystems and habitats approach or surpass critical tipping points. In the search for solutions, ocean science is indispensable. The third *World Ocean Assessment* offers the most comprehensive evaluation to date, providing Governments, institutions and the public with the evidence needed to shape coordinated, effective action.

Five years ago, the previous *Assessment* found persistent degradation of marine ecosystems. This third *Assessment* documents a deepening crisis, as climate change, pollution, overfishing and biodiversity loss put ocean systems under severe strain. Its findings demand urgent action, through stronger multilateral cooperation, greater ambition and decisions grounded in the best available science.

This *Assessment* comes midway through the United Nations Decade of Ocean Science for Sustainable Development and the United Nations Decade on Ecosystem Restoration. It takes stock of what we have learned, how far we have come and what more is needed to secure a healthy, resilient ocean for current and future generations.

The entry into force of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction in January 2026 marks a historic milestone for ocean stewardship and multilateral cooperation. Now we must translate that momentum, and the latest science, into decisive action for a healthy and resilient ocean.

May this *Assessment* strengthen our resolve to protect the ocean and, in doing so, help safeguard our climate, our food systems, our prosperity and our future.



Luis Arpa

Preface

The ocean covers more than 70% of the Earth's surface and is our largest and most interconnected ecosystem. It plays a central role in the Earth's climate and underpins societies, economies and the natural systems on which all life depends. The imperative for a healthy and resilient ocean has never been more urgent. Global collaborations and research, and the resulting increased understanding of the ocean, provide essential insights into the state of marine ecosystems, the profound changes they are undergoing and the need for our care.

The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects, was established to strengthen the science and policy interface by delivering integrated, interdisciplinary assessments of the ocean and its socioeconomic dimensions. The first *World Ocean Assessment* created a global baseline on the state of the marine environment, and the second *World Ocean Assessment* built on that foundation by identifying emerging trends and developments across the marine environment.

The third *World Ocean Assessment* was undertaken at the request of Member States, who emphasized the importance of maintaining an authoritative and up-to-date understanding of the state of the ocean. Building on the foundations laid by its predecessors, this third *Assessment* tracks evolving trends and incorporates new knowledge to meet increasingly complex policy needs.

A major development in the third *World Ocean Assessment* is the strengthened treatment of socioeconomic dimensions. The *Assessment* includes, for the first time, a stand-alone analysis of and the current framework for global and regional ocean governance, which are essential for addressing the collective management of a highly connected environment with an extensive area beyond national jurisdiction. The entry into force of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction demonstrates the global desire for the collective and equitable stewardship of the ocean, which requires robust and accessible knowledge of the ocean.

The *Assessment* extends beyond the natural sciences, incorporating insights from relevant social science disciplines. It provides detailed and specific information on the main sectors of the ocean economy and on social issues, including three cross-cutting themes: gender; equity; and Indigenous, traditional owner and local community knowledge. These themes are woven throughout the *Assessment* and are also examined in dedicated chapters. Their inclusion reflects the importance of inclusivity and of drawing on diverse knowledge to ensure that sustainable ocean stewardship benefits from the perspectives and experiences of all communities.

This *Assessment* is the result of substantial collaborative efforts undertaken over the third cycle of the Regular Process, which covered the period from 2021 to 2025. As the Group of Experts of the Regular Process, we guided and coordinated that process, ensuring the scientific integrity of the most comprehensive and authoritative global ocean assessment to date. The writing of the third *World Ocean Assessment* was carried out by more than 600 scientists from all regions of the world. These scientists were drawn from the pool of experts database of the Regular Process. Further input was provided by many other subject matter experts, including policymakers and Indigenous people, who participated in global workshops and contributed to the editing and review process. This work was made possible through the generous support of Member States and other stakeholders who contributed knowledge and facilitated regional workshops across ocean regions worldwide. We express our deep appreciation to all those who made this *Assessment* possible.

Consistent with its mandate, and following the approach of previous Assessments, the third *World Ocean Assessment* presents ocean science and knowledge in a manner that is policy-relevant but not policy-prescriptive. We hope that the insights contained in the *Assessment* will support and inspire those responsible for decision-making at all levels, providing an objective foundation for securing a sustainable future for the ocean and for all who depend on it.

Renato Andrés Quiñones Bergeret and
Rafael González-Quirós

Joint Coordinators of the Group of Experts
of the Regular Process

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Section 1
Overall summary

Key points

- The sustainable use of marine resources and services underpins environmental integrity, economic resilience and social stability, with the ocean playing a central role in regulating climate, maintaining biodiversity and providing food, minerals and energy vital to human well-being.
- However, the ocean is under mounting stress from overexploitation, pollution and the accelerating impacts of climate change, while global demand for biological, mineral and energy resources continues to grow.

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1. Introduction

The ocean covers more than 70% of the planet and is the largest and most interconnected ecosystem. It serves as the planet's primary life-support system and contains the majority of Earth's biodiversity. The ocean plays a crucial role in global nutrient cycles, particularly the carbon and nitrogen cycles, and is a major producer of oxygen.

The ocean plays a fundamental role in the evolution of climate change as part of the planet's climatic system. The ocean has already absorbed over 90% of the excess heat and 30% of the carbon dioxide (CO_2) released into the atmosphere by the anthropogenic burning of fossil fuels. Ocean currents redistribute heat at local and global scales. However, these currents are changing, and their impact on future climate change is not fully understood.

Many societies depend on the ocean directly or indirectly for their livelihood. The ocean provides a significant portion of the world's protein supply and supports industries such as shipping, tourism and renewable energy.

Cultural, spiritual and recreational values are strongly connected with the ocean. Coastal communities around the world have rich traditions and cultural identities that are tied to the ocean, whether through art, traditions or heritage. Recreational use of the ocean supports mental well-being and contributes to local economies.

2. Changes since the second *World Ocean Assessment*

The third *World Ocean Assessment* builds on previous reports and updates the second *World Ocean Assessment*, which was published in 2021 and covered the period from 2010 to 2018. Each chapter, except for the newly introduced chapters, contains specific information on the progress and changes observed primarily between 2018 and 2023. Most chapters describe all relevant information in relation to various ocean regions. The *World Ocean Assessment* now includes information on sustainability pathways and cross-cutting themes regarding gender; Indigenous, traditional owner and local community knowledge;[1] and governance.

3. Stressors on the global ocean: drivers and pressures

Drivers of ocean change

- Ocean ecosystems and the services they provide continue to be reshaped by multiple interacting drivers, including climate change, economic shifts, technological advances, governance dynamics and demographic trends.
- Understanding these drivers and their cumulative impacts is essential for designing adaptive, forward-looking policies that can safeguard biodiversity, sustain livelihoods and support a resilient blue economy.

The ocean is subject to both natural (e.g. tectonic, solar) and anthropogenic (e.g. greenhouse gas emissions, population growth) drivers, which lead to a variety of stressors and pressures (e.g. atmospheric CO_2 levels, habitat destruction and plastic pollution). Progress is being made to manage these drivers and mitigate pressures; however, many of them continue to negatively affect the ocean, especially its biodiversity, globally (see "Biodiversity and habitats" below). Although ocean hazards of natural origin are included in subsection 5B, chapter 4, of the *Assessment*, the present overall summary includes them under the subtitle "Ocean pressures" because they are natural processes that can cause significant perturbations in ecosystems and socioecological systems, and because some are mediated by climate change.

Drivers of change to the ocean (sect. 4, chap. 1)

Drivers are widely recognized (e.g. by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) or regional seas conventions) as natural or anthropogenic factors that influence ecosystem structure, function or change.

[1] The nomenclature "Indigenous, traditional owner and local community knowledge" was approved at the eighteenth meeting of the Ad Hoc Working Group of the Whole on 27 March 2023, under the annotated outline of the third *World Ocean Assessment*.

The following human drivers have the greatest influence on the marine environment:

(a) **Human population growth and demographic changes**. The global human population increased from 7.7 billion in 2017 to 8.2 billion in late 2024. Currently, approximately 37% of the global population lives within 100 km of the coast, and 11% lives on land that is less than 10 m above sea level. Population pressure heightens demand for food, space and resources, which affects the world ocean, including through habitat degradation.

(b) **Economic activity**. Global economic growth, measured as a rise in gross domestic product per capita, increased from 2.9% in 2019 to an estimated 3.3% from 2022 to 2024. Global energy consumption has accelerated from an increase of 1.5% per year around 2019 to 2.2% in 2023. Increased urbanization and industrialization have intensified the demand for energy and other resources, putting pressure on the oceans through extraction, production, consumption and waste generation.

(c) **Technological advances**. Although advances in marine technology offer opportunities, they may also have negative impacts on the world's oceans.

(d) **Changing governance structures and social, economic and geopolitical instability**. Governance is improving rapidly due to greater global collaboration, but it is also facing major global challenges. To address these challenges, governance policies, politics, administration and legislation need to be vertically and horizontally integrated globally and across sectors.

(e) **Climate change, biodiversity loss and pollution**.

The climate change suite of ocean pressures (e.g. warming, sea-level rise, acidification, marine heatwaves, storm surges and tropical storms) exhibits significant geographical variability. However, these pressures have a particular effect on the coastal domain globally, where they are coupled with other anthropogenic stressors, such as pollution and coastal urbanization. The suite of climate change ocean pressures is increasingly disrupting ecosystem dynamics and contributing to biodiversity loss. These pressures negatively affect the ocean economy, coastal activities and human well-being, health and livelihoods. Due to geographical variability and the various spatial and temporal scales at which these pressures occur, responses and strategies at all levels, from global to local, must be implemented to effectively mitigate their impacts.

Ocean pressures (sect. 4, chap. 6)

The ocean is subject to many anthropogenic pressures. As human activity is concentrated along coasts, coastal habitats suffer the greatest impact from these stressors, coupled with the effects of climate change. The combination of pressures generates cumulative effects that degrade ocean health and marine biodiversity and pose risks to human well-being.

Land-based and marine pollution sources continue to affect the ocean (see sect. 4, chap. 6). Many types of legacy contaminants (such as metals, persistent organic pollutants (POPs) and radioisotopes) and emerging contaminants (such as plastics, pharmaceutical and personal care products (PPCPs) and per- and polyfluoroalkyl substances (PFAS)) have been introduced into the ocean. There is some evidence for a decline in emissions and in precipitation of legacy contaminants such as mercury and some organic compounds in selected areas. However, POPs continue to affect many areas. Levels of pharmaceutical compounds (including antibiotics) continue to increase, particularly in coastal areas. Toxicity studies show significant adverse behavioural effects of PPCPs on marine organisms. Therefore, management action is needed to decrease the presence and potential impacts of pollution in the ocean.

The leakage of plastic waste into the ocean continues to rise globally, especially due to mismanaged waste; microplastic abrasion and loss; littering; and marine activities. There is limited understanding of nanoplastics. Microplastics affect all marine ecosystems, and there is evidence of their impact on over 4,000 species. A reduction in the production of plastics, the development of material science innovations and an increase in recycling and alternatives to single-use plastic are needed.

Global demand for nuclear electricity generation is projected to increase in the next decades as a response to the need to reduce reliance on electricity from fossil fuels. Consequently, this may lead to an increase of radioactive discharges into the ocean.

Non-indigenous species

Non-indigenous species (NIS) continue to spread through various vectors, such as maritime transport. This has significant negative impacts on native species and habitats, with further consequences for economic, social, cultural and human health. Climate change exacerbates the spread and impact of NIS by facilitating

their settlement and growth in novel locations due to changes in local environmental conditions.

Erosion and sedimentation

Since the mid-2010s, an increase in the availability of satellite data has enabled the detection of changing coastal erosion and sedimentation patterns and trends. Coastal erosion has significantly intensified in the Arctic, for instance, due to permafrost thawing and increased wave action, which are attributed to sea ice loss and longer ice-free seasons. Consequently, large quantities of nutrients have been released into the Arctic Ocean, which has implications for carbon sequestration and marine ecosystems.

Marine infrastructure

The development of marine infrastructure, particularly in areas beyond traditional coastal zones, has intensified and is exerting significant new pressures and impacts on ocean ecosystems. This development has resulted in the loss or disruption of natural habitats, affecting biodiversity. Wind farms continue to expand farther offshore, putting additional human pressure on understudied marine environments. The rate of construction of oil and gas infrastructure is also increasing, particularly in deeper waters. The installation of seafloor infrastructure, such as pipelines and cables, has a significant impact on continental slopes and submarine canyons. However, there is a growing focus on the development of proactive infrastructure strategies to facilitate adaptation to hazards, including nature-based solutions, buffer zones, physical barriers and systems for early warning and evacuation.

Cumulative effects

Since the publication of the second *World Ocean Assessment*, there has been continued recognition and research on cumulative effects and the need for coordinated management of the oceans. However, global platforms and knowledge bases for mapping human pressures and understanding their cumulative effects are lacking. The assessment of cumulative effects is crucial to preventing ecosystem deterioration.

Ocean hazards of natural origin (subsect. 5B, chap. 4)

Geophysical and geological ocean hazards of natural origin, such as earthquakes, tsunamis and volcanic eruptions, cause deaths and economic losses. Although tectonic subsidence operates on long timescales, it interacts with ocean hazards of natural origin such as flooding, storm surges and sea-level rise. These hazards are increasing or are projected to increase due to climate change. Climate change is causing coastal erosion on all continents. By 2050, one third of the low-elevation coastal zone is projected to experience a shoreline retreat of more than 100 m.

Ocean weather and hydrological and climate hazards include tropical storms, meteotsunamis, waves, sea-level rise, coastal flooding, marine heatwaves, glacial melting, heavy rainfall and river flooding, droughts, saltwater intrusion, acidification and deoxygenation. While these ocean hazards of natural origin are projected to increase or intensify with climate change, they operate over extremely variable timescales. Ocean hazards of natural origin lead to the loss of lives and land; damage to infrastructure and property; disruption of tourism, food systems and livelihoods; coastal flooding and erosion; loss of habitats and biodiversity; loss of cultural and natural heritage; navigational and shipping challenges; and water quality issues, including saline intrusion.

4. Socioecological systems (sect. 5)

One Health (subsect. 5B)

One Health, defined by the One Health High-Level Expert Panel[2] as an integrated, unified approach that is aimed at sustainably balancing and optimizing the health of people, animals and ecosystems, is a useful framework for identifying the linkages and interdependencies in socioecological systems that go beyond the human economic activities. The concept is based on several fundamental principles, including equity, inclusivity, equal access, parity, socioecological equilibrium, stewardship and transdisciplinarity. The World Health Organization (WHO) recognizes its particular relevance to food and water safety, nutrition, the control of zoonoses, the management of pollution and the combating of antimicrobial resistance.

[2] One Health High-Level Expert Panel, "One Health: A new definition for a sustainable and healthy future". *PLOS Pathogens*, vol. 18, No. 6 (23 June 2022).

Subsection 5B, entitled "One Health", of the third *World Ocean Assessment* contains a consideration of issues with strong social dimensions – such as human health, well-being, equity, gender and Indigenous, traditional owner and local community knowledge – in tandem with issues that have significant social impacts, such as the role of ecosystems in the carbon cycle, ocean hazards and the effects of the coronavirus disease (COVID-19) pandemic.

The role of marine ecosystems in the carbon cycle (subsect. 5B, chap. 1)

Blue carbon

- Mangroves, seagrasses and salt marshes – collectively, the first ecosystems to be considered coastal blue carbon ecosystems – hold higher carbon densities than terrestrial forests and host high biodiversity and associated services.
- Although their blue carbon value may be a significant financial resource according to the Paris Agreement under the United Nations Framework Convention on Climate Change, the understanding of their value is currently hampered by insufficient technical capacities for carbon accounting and financial mechanisms.
- Even with full restoration, coastal blue carbon ecosystems would only contribute 2% to the global climate mitigation targets.

The ocean contributes to approximately half of the Earth's annual primary production and supports 80% of global animal biomass. Marine ecosystems play a crucial role in driving the carbon cycle, which is linked to the health and well-being of billions of people due to its impact on climate change regulation and mitigation and their other related ecosystem services, such as food provision.

The biological pump (see subsect. 5B, chap. 1, figure I) is the process by which plankton and nekton drive carbon from the surface of the ocean to the deep sea where it is remineralized by organisms. When carbon reaches depths below 500 to 1,000 m, it becomes sequestered for hundreds to thousands of years. Although only about 2% of carbon fixed at the ocean surface reaches the deep sea, the large spatial extent of the open ocean ensures that it will continue to play a significant role in modulating climate change over decadal to centennial timescales.

However, the biological pump consists of a complex array of processes, such as sinking material versus migrating organisms, carbon dynamics within sediments and carbon export from shelf areas towards the open ocean. There is a great deal of uncertainty regarding the relative contribution of those processes and how they differ across geographical areas. Reducing these uncertainties is critical to understanding the role of the ocean as one of the major contributors to carbon sequestration.

Blue carbon ecosystems

The term "blue carbon" was first used for three vegetated coastal ecosystems – salt marshes, seagrass meadows and mangroves – which capture and store more carbon per unit area than terrestrial forests. The term has been broadened beyond these original coastal blue carbon ecosystems to include other habitats.

Unvegetated seafloor sediments on the continental shelf make up around 9% of the total marine area but store the largest amount of carbon in shelf systems. Over 80% of organic carbon is buried in these subtidal sediments.

The protection and restoration of coastal blue carbon ecosystems are recognized as nature-based solutions and an ecosystem-based approach to mitigating marine climate change. They may contribute to the achievement of nationally determined contributions under the Paris Agreement. Several countries have initiated strategies to enhance the carbon sink capacity of coastal ecosystems through targeted conservation, restoration and management. Recent estimates indicate that, with full restoration, coastal blue carbon ecosystems could contribute about 2% to the global potential for climate change mitigation.

In temperate regions, the small geographic size of these ecosystems makes it unlikely that they will play a significant role in achieving mitigation targets. However, for small island nations, which have a larger geographical extent of blue coastal habitats, the contribution may be significantly higher. Access to international financing and capacity-building, including scientific cooperation, training and the transfer of marine technology, are critical for the assessment and management of blue carbon so as to ensure that efficient methodologies are applied. These actions are already included in various nationally determined contributions and are necessary to achieve global targets.

Macroalgae have recently been suggested as a coastal blue carbon ecosystem. While most algal production is remineralized annually, a fraction is potentially exported to the open ocean or buried in sediments.

While it may seem counter-intuitive, calcification by marine organisms, such as corals and bivalves, gives rise to a net emission of CO_2, and, in addition, many calcifiers produce CO_2 through respiration. Recently, coralline algal beds found in sediments have been proposed as blue carbon habitats because the carbon captured and stored through photosynthesis may exceed the CO_2 released by calcification.

Ocean and human health (subsect. 5B, chap. 2) and human well-being (subsect. 5B, chap. 3)

Human well-being and health

- Oceans contribute to human well-being by providing a wide range of non-market benefits, including mental and physical health gains, cultural identity, spiritual fulfilment, recreation and community cohesion. However, these contributions are under increasing pressure from climate change, pollution, habitat loss and unsustainable exploitation, reducing the ocean's capacity to sustain people and nature.
- Human well-being and health both benefit from policies that connect conservation with equitable access, incorporate both market and non-market values, enable community-led stewardship and provide sustainable pathways for balancing human needs with ecosystem health.

The health of the ocean and that of human populations are deeply interconnected. There are many ways in which the ocean has a positive impact on human health. For example, there are benefits related to ocean sporting activities, the consumption of seafood and the development of marine-derived pharmaceutical compounds. Well-being is also associated with the therapeutic and restorative qualities of marine environments, reinforcing the significance of accessible blue spaces for mental and physical health.

Ocean ecosystems contribute greatly to human well-being in ways that extend beyond health. These contributions include economic value and non-market benefits such as spiritual, cultural and recreational services.

The non-market valuation of marine ecosystems, despite its challenges, is crucial for understanding and quantifying the non-monetary value of the ocean, which can enable policy decisions that support both human well-being and environmental health.

Ocean ecosystems play an irreplaceable role in supporting cultural practices, traditional knowledge, intergenerational heritage and social cohesion. This is particularly critical in the case of Indigenous Peoples. Communities interact with and depend on ocean resources, often employing innovative strategies to balance conservation with socioeconomic needs.

The health and well-being benefits derived from ocean ecosystems are at risk due to escalating environmental challenges such as climate change, pollution and resource depletion. Human health is increasingly challenged by harmful algal blooms, pathogenic bacteria and viruses, antimicrobial resistance and toxic chemicals. In addition, environmental radiation can further threaten marine ecosystems. Contaminated seafood poses serious food safety risks and may cause endocrine disruption, neurotoxicity, renal dysfunction, osteoporosis and various cancers.

The integration of cultural, economic and ecological perspectives into ocean management policy ensures that the ocean continues to support human health benefits and well-being, cultural and natural heritage and sustainable development for future generations.

Pandemics, including COVID-19 impacts (subsect. 5B, chap. 7)

The COVID-19 pandemic resulted in a mixture of some short-term environmental benefits due to reduced human activity, alongside severe negative consequences for ocean-dependent communities and economies and a rise in pollution levels. The COVID-19 pandemic had severe impacts on the health and safety of seafood workers and coastal communities. High infection risks, declining demand for seafood and a decrease in global tourism disrupted business activities related to fisheries, port operations and supply chains. Many fishing- and tourism-dependent industries and communities faced significant financial losses, leading to increased unemployment and financial insecurity.

The COVID-19 pandemic reduced ocean use, which reduced noise and improved reproduction for some species (e.g. whales). However, the pandemic also negatively affected marine ecosystems. Increased plastic waste, particularly from discarded face masks, threatened marine species. The pandemic also resulted in an increase in the use of specific medications and treatments, resulting in a higher concentration of pharmaceutical residues in marine environments.

Disruptions in scientific research and fisheries monitoring fuelled illegal fishing in certain regions. Due to the

pandemic, many new policies were created to address health and safety issues (e.g. workplace safety) in ocean-related employment. Many direct and indirect effects of the COVID-19 pandemic remain unknown, underscoring the need for further research to prepare for future global health crises.

Trends in the physical and chemical state of the ocean (sect. 4, chap. 3)

Physical and chemical changes

- The alteration of the physical and chemical conditions of the ocean due to climate change is accelerating.
- Approximately 16% of the total increase in ocean heat content since 1955 has occurred since 2018. The greatest relative warming has been observed in the Atlantic Ocean and the southern parts of the Indian and Pacific Oceans.
- The sea level continues to rise at increasing rates, from less than 2.0 mm per year prior to 2015 to 4.3 mm per year in 2023. Tropical seas are rising more rapidly due to thermal expansion.
- The extent of Arctic sea ice continues to decrease, and the Southern Ocean has recently shown declines in sea ice extent. The Arctic Ocean could become entirely ice-free in September by the middle of the twenty-first century.
- Ocean CO_2 uptake and ocean acidification continue to increase, although these trends exhibit high spatial and inter-annual variability due to weather and climate conditions.
- Global ocean deoxygenation persists due to rising water temperature (which reduces oxygen solubility and increases stratification) and intensified microbial activity caused by nutrient run-off from land. Ocean hypoxic zones continue to expand (covering an additional 4.5 million km^2 in the past 50 years).

The ocean continues to capture and store energy and is warming at accelerated rates. Some 16% of the ocean heat content increase from 1955 has occurred since 2018.

Salinity varies greatly across the globe depending on the amount of freshwater input and evaporation; there is no significant global trend in that regard. Since 2018, salinity has decreased in the Pacific, North Atlantic and Southern Oceans but has increased notably in the mid-southern Atlantic and northern Indian Oceans.

The sea level continues to rise at an increasing rate (2.0 mm per year prior to 2015; 4.3 mm per year in 2023) due to thermal expansion (especially in tropical regions) and the melting of ice in polar regions. Additional variability is due to storm surges and tectonic and isostatic processes.

The extent of Arctic sea ice continues to decrease, and the Arctic Ocean could become entirely ice-free in September by the middle of the twenty-first century. Currently, the decrease is more apparent in areas influenced by Atlantic and Pacific waters. The decrease of sea ice is resulting in changes to vertical stratification and mixing and further influencing circulation patterns. Southern Ocean sea ice, which until recently showed a regionally contrasting response to predominantly atmospherically driven changes, now shows Antarctic-wide declines in sea ice extent, which in turn are resulting in changes in dense shelf water production and associated Antarctic Bottom Water formation.

The weakening of the Atlantic Meridional Overturning Circulation is of particular concern due to its potential impact on the climate of the northern hemisphere, especially Europe. None of the recent models implemented by the World Climate Research Programme predict the collapse of the Atlantic Meridional Overturning Circulation during this century, and the confidence level regarding its weakening is medium to low. This contrasts with previous World Climate Research Programme results that had predicted a slowdown of the Atlantic Meridional Overturning Circulation, with some models predicting an abrupt collapse during the twenty-first century. However, other studies have found that the Atlantic Meridional Overturning Circulation is weakening and could reach a tipping point with an abrupt collapse by the middle of the twenty-first century. Atlantic Meridional Overturning Circulation remains a research priority.

Between 1986 and 2022, ocean pH declined by approximately 0.06 to 0.10 units, with significant decreases observed at depths down to 2,000 m. Ocean CO_2 uptake is responsible for the decrease in pH and is highly variable spatially and temporally, but has tripled in the past 60 years (1960–2019), reaching 2.7 ± 0.3 petagrams of carbon per year as of 2019. This value is expected to increase by 0.4 ± 0.1 petagrams of carbon per decade. However, this increase will be attenuated as the rise in temperature reduces CO_2 absorption. Total alkalinity, which is a measure of the capacity of the ocean to buffer acidity, has increased in subtropical regions but varies greatly across the globe.

Global ocean deoxygenation persists due to the combination of increased nutrient pollution, rising water temperatures and intensified microbial activity. Higher water temperatures decrease oxygen solubility and increase ocean stratification. This restricts the vertical exchange of gases, heat, salt and nutrients between surface, intermediate and deep waters, thereby slowing deep ocean ventilation. Ocean hypoxic zones continue to expand (covering an additional 4.5 million km^2 in the past 50 years), and the ocean continues to lose approximately one gigaton of oxygen per year.

Historical nitrogen data reveal differing trends across regions, most likely due to interactions between climate change and other anthropogenic sources and pressures. Recent phosphorus trends deviate from historical baselines, and climate change is expected to increase silica availability in the short term and decrease it in the long term (i.e. in around 150 years), but no global trends have been observed yet. These results demonstrate the need for updated monitoring and for an understanding of these complexities so that future biogeochemical cycles can be accurately predicted.

Biodiversity and habitats

- Anthropogenic, climate and other pressures are causing increasing adverse effects among all the marine taxonomic groups and habitats, from microbes to marine mammals and from the abyssal plains to the coastline.
- Climate change continues to produce impacts across the oceans, especially in high latitudes, where temperature increase and sea ice retreat are causing poleward distribution shifts across all taxa and affecting the dynamics of habitats such as high-latitude ice and fjords.
- Climate-change-related extreme events (e.g. cyclones, marine heatwaves or storm surges) occur across all latitudes, and are affecting many habitats, such as coral reefs which are declining rapidly.
- Coastal habitats are, in general, heavily affected by the accumulated impacts of climate change, contamination (including plastics), coastal development, invasive species and nutrient upload.
- Land-use changes and dam construction have drastically changed sediment fluxes, leading to coastal retreat in deltas and estuaries.
- Mangroves, seagrasses and salt marshes are declining worldwide due to pressures such as coastal or aquaculture development, contamination, eutrophication, storm surges, cyclones and invasive species.
- The deepest parts of the ocean (e.g. trenches and abyssal areas) are difficult to access, are poorly understood, lack detailed mapping and is increasingly under pressure as a potential site of resource (e.g. mineral) extraction.
- A diverse array of marine protected areas (MPAs) are being developed and approved as part of marine spatial planning across the globe. International stakeholders are working to establish the first "blue corridors", or large-scale MPAs, to protect and ensure the long-term health of biodiversity.

Marine biodiversity (sect. 4, chap. 4)

Marine biodiversity encompasses the variety of life forms within ocean ecosystems, and ranges from microbes to large marine mammals. Biodiversity is critical to biological productivity, carbon cycling and climate regulation.

All marine life interacts in complex ways, providing resilience and stability to ecosystems. Since the second *World Ocean Assessment*, marine biodiversity has undergone significant changes, influenced by increasing pressures that are contributing to the worsening global biodiversity crisis. These changes have affected the resources and services provided by marine ecosystems to society worldwide.

Plankton (see sect. 4, subchap. 4A) is the foundation of the pelagic food web and of shelf and deep-sea benthic habitats. It plays a fundamental role in biogeochemical cycles and supports higher trophic levels, including those sustaining fisheries.

The most dramatic changes since the publication of the second *World Ocean Assessment* have been observed in the Arctic Ocean. The increase in phytoplankton biomass is associated with a warming climate and decreasing sea ice coverage, and changes are occurring with respect to the abundance, composition, phenology and distribution of phytoplankton. Globally, phytoplankton blooms are unpredictable and can disrupt carbon cycling and the accessibility of food for higher trophic levels. Zooplankton populations, especially krill, have demonstrated regional declines. The impacts of climate change on plankton in many regions remain unclear, largely due to the limited availability of long-term observational time series.

Cephalopods demonstrate resilience in the face of climate change due to their short life cycles and high

reproductive rates, with some populations thriving as a result of increasing temperatures. Nevertheless, distribution patterns have changed, and certain exploited species consistently face pressures from fisheries.

Marine benthic invertebrates (see sect. 4, subchap. 4E), particularly corals, are experiencing increased stress due to the increase in widespread bleaching events caused by elevated sea temperatures. Despite the positive effects observed from conservation efforts and MPAs since the publication of the second *World Ocean Assessment*, there is still a lack of knowledge about deep-sea species, and they remain vulnerable to destructive activities such as trawling.

Fish populations (see sect. 4, subchap. 4D) consistently face challenges due to overfishing and habitat degradation, despite improved fisheries management and reductions in by-catch. While many species of reef fish continue to decline in numbers, some, such as tuna, show signs of recovery because of improved fisheries management measures.

Marine mammals (see sect. 4, subchap. 4E) face persistent risks, including entanglement in fishing gear, collisions with vessels and ingestion of plastic pollution. While some species (e.g. Mediterranean seals and dolphins) have shown slight recovery, others, such as the North Atlantic right whale, remain critically endangered. Moreover, increased underwater noise pollution (e.g. from armed conflict, shipping or offshore infrastructure) is disrupting marine mammal migration and communication.

Marine reptiles (see sect. 4, subchap. 4F), particularly sea turtles, struggle as a result of habitat loss, plastic pollution and climate change. While conservation efforts have led to improved nesting success, general trends are alarming, especially as increasing sand temperatures mean that hatchling sex ratios are skewed towards females.

Climate change similarly affects seabirds (see sect. 4, subchap. 4G), as changes in prey availability influence their reproductive success. Plastic ingestion and by-catch-related mortality have increased, although some bird species have experienced reduced mortality due to modified fishing techniques.

Marine plants (see sect. 4, subchap. 4H), including seagrass and mangrove ecosystems, are essential for coastal protection and serve as key habitat that support marine biodiversity. Pollution and coastal development continue to affect them and reduce their coverage area. Following the publication of the second *World Ocean Assessment*, their climate-mitigating properties have become better known, spurring the development of restoration projects. Macroalgae (see sect. 4, chap. 4I), such as kelp forests, have diminished due to rising water temperatures and changing herbivore populations. While some regions have shown resilience due to conservation efforts, invasive macroalgae increasingly threaten native biodiversity.

Overall, the key findings of the third *World Ocean Assessment* underscore that persistent challenges, including climate change, habitat loss, pollution (particularly from plastics) and overexploitation, confront marine biodiversity. Conservation efforts, strengthened regulations and global cooperation are crucial for mitigating these impacts and preserving the resilience of marine ecosystems.

Habitats (sect. 4, chap. 5)

Marine habitats encompass diverse ecosystems, ranging from shallow coastal zones to deep-sea environments. These habitats are vital for maintaining biodiversity, providing ecosystem services and supporting human livelihoods. However, they are increasingly affected by pollution, habitat loss, climate change and human activities. Sea-level rise, ocean acidification, increased extreme climatic events and habitat fragmentation have all contributed to changes in a variety of marine habitats since the publication of the second *World Ocean Assessment*. At the same time, conservation efforts have grown, with a focus on nature-based solutions, ecosystem restoration and sustainable management techniques.

The intertidal zone (see sect. 4, subchap. 5A) continues to experience significant transformations and habitat loss caused by sea-level rise and coastal squeeze. Eutrophication and pollution, including from microplastic accumulation, affect species and ecosystem services. Attempts to use intertidal ecosystems to mitigate climate change have increased. Conservation strategies increasingly use green-grey infrastructure, ecosystem co-design and nature-based solutions.

Biogenic reefs and sandy, muddy and rocky shores (see sect. 4, subchap. 5B) face intense pressures that threaten biodiversity and disrupt ecosystem functions. Coastal squeeze and human infrastructure already affect 33% of global beaches, with up to 26% at risk of severe sand loss by the century's end. Emergent threats such as plastic pollution (see sect. 4, chap. 6) and artificial light at night

further strain these environments, requiring target research and mitigation strategies. Safeguarding coastal habitats requires robust governance that integrates diverse knowledge systems (e.g. Indigenous, traditional owner and local community knowledge) and encourages participatory decision-making. Greater research is needed in tropical and subtropical regions, where data gaps persist, while addressing disparities in coastal management between high- and middle-income countries.

New understanding of atolls (see sect. 4, subchap. 5C), including through the antecedent karst theory and hydrogeology, is challenging previous models of atoll formation. Carbonate sand production and storm-driven sediment transport may help to sustain atoll islands in the face of rising sea levels. Atolls face ocean acidification and warming seas, which weaken reefs and increase coral bleaching. While some remote reefs recover within years, densely populated atolls take over a decade to regenerate. This reinforces the importance of integrated conservation approaches.

Coral reefs (see sect. 4, subchap. 5D) around the world are declining rapidly due to various stressors. Increasing disturbances, such as marine heatwaves and storms, leave little time for recovery and are pushing reefs towards collapse. Since 2018, multiple global bleaching events have caused widespread coral mortality. Projections suggest that 90% of reefs could disappear if warming exceeds 1.5°C above pre-industrial levels. Even historically resilient areas, such as the South Atlantic, are experiencing severe losses. Rising hypoxia and ocean acidification add further stress. The Caribbean has lost 80% of its coral cover since the 1970s.

Although cold-water corals and sponges (CWCS) (see sect. 4, subchap. 5E) face increasing threats, new discoveries, such as the extensive reefs on the Blake Plateau, highlight their role in carbon sequestration and ecosystem dynamics. Ocean acidification continues to weaken coral structures and further severe declines are predicted under high-emission scenarios. While advances in CWCS ecology improve the understanding of these fragile ecosystems, long-term monitoring and policy integration remain limited. Expanding protection and global research efforts are urgent priorities.

Changes in estuarine and deltaic environments (see sect. 4, subchap. 5F) have significantly altered sediment dynamics, water quality and ecosystem structures. Since the publication of the second *World Ocean Assessment*, drastic changes in land use and the construction of dams have altered sediment fluxes, resulting in accelerated coastal retreat and subsidence in many areas.

Seagrass meadows (see sect. 4, subchap. 5G) are essential for carbon sequestration, habitat biodiversity and coastal protection. They are declining worldwide, with an overall decline of around 29% since the late nineteenth century. Since the publication of the second *World Ocean Assessment*, marine heatwaves, storms and sea-level rise have intensified these declines, especially in East and South-East Asia and certain regions of the North Atlantic. A large area (covering between 66,000 and 92,000 km²) of seagrass beds was discovered in The Bahamas. Major gaps remain, including the need for an update of the global seagrass map, inadequate mapping in deep or turbid waters, insufficient comprehension of climate resilience and carbon sequestration rates, and an absence of conservation policies.

Mangroves (see sect. 4, subchap. 5H) offer important ecosystem services such as coastal protection, biodiversity and carbon sequestration, with an estimated economic value of $65 billion annually. Between 2010 and 2020, net annual mangrove loss declined to 102.4 km², primarily due to conservation efforts, compared with the previous decade. However, losses persist due to aquaculture, urbanization and sea-level rise. Notable restoration projects include the goal of China to restore 18,800 ha by 2025, the goal of Indonesia to restore 600,000 ha by 2024 and the initiative of the Islamic Republic of Iran to plant 1,000 ha of mangrove forests.

Coastal development, pollution, sea-level rise and invasive species are causing salt marshes (see sect. 4, subchap. 5I) to decline globally. Since the publication of the second *World Ocean Assessment*, losses have continued steadily, with some areas experiencing mangrove encroachment driven by climate change. Although oil and chemical pollution have decreased, the accumulation of plastic is now a major concern.

Continental slopes and submarine canyons (see sect. 4, subchap. 5J) are increasingly affected by direct anthropogenic impacts and by climate change. Fishing, waste dumping, litter and plastic pollution, oil and gas exploration and exploitation, the installation of seafloor infrastructure, noise generation and tourism appear to be the human activities that have the most impact. Despite substantial advances in slope and canyon knowledge, conservation and management, many of the gaps identified in the second *World Ocean Assessment* remain. Most continental slope and submarine canyon

habitats remain unexplored and long-term data are limited, making it difficult to assess changes over the past 5 to 10 years.

Since the publication of the second *World Ocean Assessment*, significant changes have taken place in high-latitude sea ice (see sect. 4, subchap. 5K). Arctic sea ice continues to decline, and an ice-free Arctic in September is likely within the next few decades. Meanwhile, Antarctic sea ice, which had gradually increased from 1979 to 2015, has rapidly declined since 2016, possibly indicating a regime shift.

Seamounts and pinnacles (see sect. 4, subchap. 5L) are submerged mountains that support distinctive deep-sea biodiversity, including corals, sponges and economically valuable fish species. Deep-sea fisheries are increasingly exploiting these ecosystems, resulting in habitat degradation. Since the publication of the second *World Ocean Assessment*, conservation initiatives have intensified, resulting in enhanced protection of seamounts by means of MPAs and heightened recognition of their ecological significance. However, despite significant improvements, the understanding of ecosystem dynamics in abyssal seamounts, in seamounts found in areas beyond national jurisdictions and in population connectivity between seamounts remains limited.

Abyssal plains (see sect. 4, subchap. 5M), which are extensive deep-sea areas, are the most understudied marine habitats on Earth. These regions host unique species adapted to extreme conditions and contribute to global carbon cycling. An increasing potential threat from deep-sea mining for rare minerals raises concerns about the resulting potential for habitat destruction and biodiversity loss.

The pelagic domain (see sect. 4, subchap. 5N) is the largest habitat on Earth and plays a crucial role in global climate regulation, carbon cycling and biodiversity. Since the publication of the second *World Ocean Assessment*, advancements in observational technologies and environmental DNA techniques have enabled extensive data collection and supported multidisciplinary studies. The latest Earth system models from the Coupled Model Intercomparison Project have projected greater warming, acidification, deoxygenation and nitrate reductions in the ocean, while new ecological studies, such as trophic amplification, show declining biomass in higher trophic levels.

Recent advances in deep-sea research highlight significant progress in hadal trench exploration (see sect. 4, subchap. 5O), facilitated by new technologies, while progress on exploration of ridge systems remains limited. Since the publication of the second *World Ocean Assessment*, significant findings on mid-ocean ridges have highlighted key areas of biodiversity and the impacts of human activities. The Mid-Atlantic Ridge, for example, exhibits high biodiversity that supports a wide variety of demersal fish and benthic invertebrates. The Arctic Mid-Ocean Ridge, however, faces notable impacts from fishing, mineral extraction and bioprospecting.

Hydrothermal vents and cold seeps (see sect. 4, subchap. 5P) host high levels of microbial and animal biomass that is supported by chemosynthesis and contribute to higher productivity, including of fisheries, in the surrounding systems. Technological advances have enabled the discovery of thousands of these sites in the past, as well as the development of deep oil, gas and gas hydrate activities (seeps) and new mining exploration contracts (vents) issued in the Atlantic and Indian Oceans. Additional pressures on these ecosystems include global warming, deoxygenation, ocean acidification and altered circulation, deep-sea fishing, waste dumping and plastic debris. Conservation actions taken to date include the development of scientific and industry codes of conduct and spatial protection as vulnerable marine ecosystems, MPAs, ecologically or biologically significant areas and the designations on the Red List of Threatened Species of the International Union for the Conservation of Nature and Natural Resources (IUCN).

The Sargasso Sea (see sect. 4, subchap. 5Q) is an iconic high-seas ecosystem that is internationally recognized as a crucial part of the global ocean. Since the publication of the second *World Ocean Assessment*, significant environmental changes have been observed in the Sargasso Sea due to climate change, oceanographic shifts and human activities. Ship traffic in the Sargasso Sea has increased over time.

The fjord systems (see sect. 4, subchap. 5R) of the world are characterized by a deep basin that is connected directly or indirectly to the open sea at the mouth. They are specifically identified as carbon cycle hotspots. Fjords play a crucial role in regulating the carbon cycle over time due to their effectiveness in burying organic matter. Climate change is already affecting both northern and southern hemisphere fjords via warming, deoxygenation and acidification. The loss of glacier ice and the changing seasonality of the hydrological cycle is affecting physical and chemical factors and processes in fjord systems.

Marine food systems

- Seafood sourced from wild fisheries and marine aquaculture accounts for around 20% of the animal protein and 6.7% of the total protein consumed by humans worldwide.
- Fair, transparent and sustainable trade frameworks will help to safeguard small-scale producers, ensure traceability and legality and align seafood markets with climate, biodiversity and food security goals.
- Sustainable seafood processing is a critical lever for enhancing food security, economic resilience and social equity in ocean economies. This includes integrating circular economy approaches, such as the use of renewable energy, the utilization of by-products and the reduction of emissions.
- Although aquaculture is facing many challenges, including social acceptability, pollution and climate change, it continues to adapt and grow and is increasingly important to ocean economies and essential to food and nutrition security.
- Production from marine capture fisheries has remained relatively stable. However, the proportion of global fishery stocks within biologically sustainable levels has continuously declined.
- Progress is being made across regions with respect to fisheries governance structures and management.
- Sustainable pathways for small-scale and subsistence fisheries must address the cumulative effects of multiple drivers (e.g. social, economic, environmental and climate drivers) of vulnerability, build on the knowledge and experience of fishers and address their concerns about equity, human rights and security.
- Approximately 121 million people worldwide participate in marine recreational fishing. This widespread activity has substantial positive and negative economic and ecological impacts, especially on coastal ecosystems.

Food systems must ensure global food security and nutrition for a population that is expected to reach nearly 10 billion by 2050. Despite its large extent, the ocean provides only 4–8% of human food. Food systems are not only highly dependent on the environment; they also exert significant pressure on it. Close to half a billion people are directly employed in fishing processing and related value chain activities. Sustainable wild fish and mariculture production is the foundation for sustainable trade of marine foods. The uneven geographical distribution of marine resources has historically driven trade from local to global scales, but the proportion of marine production that is exported has increased in recent decades.

Climate change is reshaping the global distribution of seafood. While interregional trade remains dominant for many regions, Asia has become an increasingly important destination. Although trade regulations, certifications and traceability tools are emerging to support sustainable trade of marine foods, unknowns remain regarding their impact and effectiveness.

Due to the high perishability of fish and fishery products and their importance for food, nutrition security and global trade, effective processing techniques are essential for extending shelf life, increasing revenues and enhancing nutritional value (see subsect. 5A, subchap. 1E). In 2022, of the 165 million tons of fish destined for human consumption, about 43% was live, fresh or chilled. This was followed by frozen (35%), prepared and preserved (12%) and cured (10%). This represents about 89% for direct human consumption, with the remaining 11% for non-food purposes such as fishmeal for aquaculture and biofuel.

Since the publication of the second *World Ocean Assessment*, significant progress has been made in prioritizing seafood and aquatic food systems within the United Nations Decade of Ocean Science for Sustainable Development and the Sustainable Development Goals of the 2030 Agenda for Sustainable Development. Technological advances in seafood processing have great potential to promote sustainable growth and food security and to contribute to the conservation of marine ecosystems. As global demand for seafood increases, integrated policy frameworks and value chain improvements must be aligned to foster a more inclusive and resilient industry. Advanced processing techniques, particularly in the areas of traceability and rules of origin, will play a key role in ensuring compliance and meeting the diverse needs of stakeholders. By addressing some of the social and economic issues in coastal communities, the seafood processing industry can play a central role in promoting gender inclusion, fair wages and decent working conditions for all.

Due to uncertainties and a lack of global disaggregated data on small-, medium- and large-scale aquaculture, it is difficult to segregate the contributions and impacts of each subsector (see subsect. 5A, subchaps. 1C and 1D). In the second *World Ocean Assessment*, medium- and large-scale aquaculture refers to commercial orientated production for domestic or export markets, conducted

by companies ranging from medium-scale enterprises through to large-scale multinational companies. Between 2018 and 2022, marine aquaculture production increased from 55.7 million tons to 60.2 million tons, and the overall value increased from $76 billion to $89.2 billion.

Over the past two decades, aquaculture production has increased at a rapid pace, and the sector has become more integrated into the global food system. There have been many improvements in farming methods in medium and large-scale aquaculture, as well as major developments throughout aquaculture value chains, with aquaculture products now among the most globalized food items. Digitalization and emerging technologies (e.g. blockchain) are playing an increasingly important role in medium and large-scale aquaculture production. Increased attention has also been paid to the farming of low-trophic marine species, including large-scale molluscs and algae. However, issues of social acceptability and environmental impact must be addressed if the sector is to increase production significantly.

Over the past decade, significant efforts have been made to reduce dependence on antibiotics in aquaculture, in particular due to the potential for antimicrobial resistance and its impact on human health. With respect to feed aquaculture (e.g. fish and shrimp), concerns remain about the use of fishmeal and fish oil, overexploitation of wild stocks and feed-food competition.

Climate change also poses challenges for medium and large-scale aquaculture production and the supply chain. Climate-related events affecting marine aquaculture include marine heatwaves, harmful algal blooms, deoxygenation and storms. There is a need to focus more efforts on adapting aquaculture production to and mitigating climate change.

The assessment of small-scale aquaculture in subsection 5A, subchapter 1D, involves consideration of two distinct practices: (a) nearshore marine aquaculture (NSMA) and (b) coastal marine aquaculture (CMA). The latter is typically practised in constructed ponds onshore or in intertidal zones. Small-scale aquaculture plays a significant role in global food security, livelihoods, nutrition and health. On a global scale, most of the world's small-scale production of seaweed, sea cucumbers and sea molluscs are from NSMA, while crustacean production primarily takes place in onshore coastal brackish water ponds and tanks. CMA is dominated by brackish water shrimp and a few species of fish, crayfish and crabs. Some species (e.g. seaweeds and molluscs) and well-managed practices in small-scale aquaculture have a low impact on the health of the ocean.

However, given the potential negative impacts of the aggregation of small-scale aquaculture operations, spatial planning and the consideration of carrying capacity limits should be promoted at the national and regional levels. Over the past several decades, NSMA and CMA have experienced major disease outbreaks. Best management practices, including biosecurity measures, should be implemented to protect the activity and make small-scale aquaculture more sustainable with the least negative impact on the health of the ocean. NSMA and CMA cannot be sustainable without addressing the impacts of climate change and of stressors from land-based sources. In addition, the communities involved in NSMA and CMA are relatively poor and have limited resources, which limits their resilience to climate change.

Small-scale fisheries (see subsect. 5A, subchap. 1B) are of high social, economic, cultural and environmental importance and play a critical role in fostering food and nutrition security for millions of people. Small-scale and subsistence fisheries contribute significantly to national and global economies and are of great social and cultural importance. However, small-scale fisheries are under increasing pressure from declining fish stocks and competition from industrial fisheries. The cumulative effects of a wide range of environmental stressors and climate drivers pose significant threats to the viability and resilience of small-scale fisheries and subsistence fisheries in many regions of the world.

Large-scale fisheries and medium-scale fisheries (see subsect. 5A, subchap. 1A) differ in scale and scope of operations, each with its own set of practices, impacts and sustainability measures. While medium-scale fisheries play a vital role in supporting local economies and livelihoods, large-scale fisheries operations often have broader environmental and economic impacts that demand careful management and regulation. The third *World Ocean Assessment* emphasizes the importance of ecosystem-based management, transparency, traceability and stakeholder collaboration to mitigate the negative impacts of medium-scale and large-scale fisheries.

Overfishing and illegal, unreported and unregulated (IUU) fishing are among the most pressing concerns when it comes to the sustainable use of the ocean resources. The fraction of global fishery stocks within biologically sustainable levels decreased to 62.3% in 2021, down from 64.6% in 2019, while many others are reaching their full

exploitation or are in decline. It is estimated that, globally, between 8 million and 14 million metric tons of unreported catch are illicitly traded each year, representing gross revenues of $9 to $17 billion per year. In addition to the damage to fish populations and ecosystems caused by IUU, the estimated annual economic impact loss due to the diversion of fish from the legitimate trade system is estimated to be between $26 billion and $50 billion.

Marine recreational fishing (see subsect. 5A, chap. 2) is defined as fishing of marine animals (mainly fishes) that are not the individual's primary source for meeting basic nutritional needs and that are not generally sold or otherwise traded on export, domestic or black markets. Marine recreational fishing contributes billions of dollars annually, especially in developed countries, to local communities through job creation and the promotion of marine stewardship. It is estimated that 121 million people worldwide participate in marine recreational fishing. While the total estimated global marine recreational harvest is about 1% of total commercial landings, recreational removals are generally concentrated in a narrow band of coastal areas, and the impacts are most intense at the local level. The lack of formal recognition of the marine recreational fishing sector is a fundamental problem in fisheries management, contributing to overfishing, conflicts with commercial and subsistence fishers and reduced societal benefits from recreational fisheries. Addressing data gaps, stakeholder collaboration, socioeconomic integration and compliance through education and normative approaches are essential for the effective management of marine recreational fishing and obtaining societal benefit from it.

Sustainable resource use, goals and pathways

- Offshore oil and gas production is continually increasing and accounts for nearly one third of global output, with deepwater and ultra deepwater reserves driving recent exploration growth.
- Although oil spill incidents are trending downward, they cause prolonged ecological disruption, with hydrocarbons persisting in food webs and affecting health, reproduction and population dynamics.
- While offshore renewable energy (ORE) contributes to the global energy transition and to decarbonizing the economy, its implementation requires careful consideration of environmental impacts.
- Over 80% of global trade by volume is shipped by sea. Decarbonizing the shipping sector is crucial because greenhouse gas emissions from ships contribute around 3% of global emissions.
- Tourism in coastal and ocean regions contributes over $5.5 trillion annually and supports approximately 174 million jobs, making it the most significant sector of the ocean economy.
- Tourism can negatively affect the marine environment, but there is a growing role for nature-positive, community-based tourism models that are supported by targeted investments in ecosystems, cultural heritage and inclusive governance.
- Socioeconomic inequalities are reported in many coastal regions, where ocean-dependent communities, particularly women and Indigenous Peoples, often face limited access to markets, capital and technology.
- Equity in ocean governance is essential to ensuring that the benefits, responsibilities and opportunities of ocean use are shared fairly among all stakeholders, including women, youth, Indigenous Peoples and marginalized communities.
- Including gender perspectives into ocean governance enhances the resilience and effectiveness of conservation and management initiatives.

Sustainable resource use refers to the management of ocean resources in a manner that satisfies present needs without compromising the ability of future generations to meet their own needs. The sustainable use of natural resources is key to global environmental, economic and social stability. The ocean plays an essential role in this process by regulating the climate, maintaining biodiversity and providing critical resources for humanity, such as food, minerals and energy.

Observed trends in ocean renewable (see subsect. 5A, subchap. 3A) and non-renewable (see subsect. 5A, subchap. 3B) technology developments include offshore wind farms and tidal and wave energy systems. While renewable-energy developments are focused on efficiency and cost reduction, efforts to explore non-renewable-energy sources continue despite concerns about potential adverse environmental impacts. However, more sustainable approaches are emerging.

Emerging trends, such as increased global interest in ORE and growing awareness of the importance of ocean conservation, present opportunities and challenges. As the world moves towards a more sustainable future, it is essential to balance the benefits of using ocean

resources with the necessity of protecting marine ecosystems and securing social equity.

Despite its many positive aspects for humans, the rapid growth of coastal tourism (see subsect. 5A, chap. 4) can also lead to habitat destruction, pollution and the overexploitation of marine resources, such as coral reefs and fish stocks. Unsustainable tourism contributes to marine pollution, including plastic waste, noise and the hazard of oil spills, which harm marine life. Overcrowding at popular destinations can degrade local ecosystems and adversely affect the well-being of coastal communities. Emerging sustainable tourism practices, such as responsible waste management, eco-friendly infrastructure and community-based conservation, are crucial to mitigating these impacts and securing sustainability.

Shipping (see subsect. 5A, chap. 6) accounts for more than 80% of all world trade in goods by volume. It plays a critical role in global commerce by enabling the movement of goods and connecting businesses with customers worldwide. However, the global shipping fleet accounted for approximately 3% of total global greenhouse gas CO_2 emissions in 2023, and estimates show that this figure could increase by 90–130% above 2008 levels by 2050. In times of unprecedented climate and environmental changes, sustainable shipping is of critical importance. Examples of sustainable approaches include the use of cleaner fuels, the use of technologies that reduce carbon emissions and the optimization of shipping routes to minimize environmental impact.

About 90% of commercial vessels use bunker fuel, a highly polluting energy source. This makes it difficult to significantly reduce emissions in the near future, as more than 70% of newly planned ships will continue to use traditional fuels. In addition to greenhouse gas emissions, shipping causes other types of environmental pressure, including chemical, biological and energy pollution. Therefore, environmental regulations, driven by concerns about pollution and climate change, are becoming increasingly rigorous.

Ocean water desalination and salt production (see subsect. 5A, chap. 8) are increasingly reliant on renewable energy, applied to support desalination plants. Technologies based on reverse osmosis and electrodialysis are improving efficiency. Salt production methods worldwide are rapidly evolving towards sustainable practices.

Since the publication of the second *World Ocean Assessment*, the search for and use of marine genetic resources (see subsect. 5A, chap. 5), as well as the development of marine biotechnology, have continued to grow rapidly. Advances in marine genomics have led to many discoveries in the fields of sustainable bioproducts, pharmaceuticals and biofuels. Although marine genetic resources hold immense potential, they remain largely understudied. Most areas beyond national jurisdiction, including the deep sea, are still unexplored.

Mineral resources

The exploration and exploitation of marine mineral resources in maritime areas under national jurisdiction have been driven by demand. While deep-sea mineral exploration has occurred both within and beyond national jurisdiction, commercial exploitation has not begun. The sustainable exploration and potential exploitation of marine mineral resources depend on scientific and technological innovation, stakeholder participation and reliable information to effectively evaluate environmental, social and economic impacts (see subsect. 5A, chap. 7).

Socioeconomic inequalities are reported in many coastal regions, where ocean-dependent communities, particularly women and Indigenous Peoples, often face limited access to markets, capital and technology (see subsect. 5B, chap. 5). Therefore, policies aimed at creating an inclusive ocean economy should emphasize social equity, access to resources and the participation of persons in marginalized situations in decision-making processes.

While ocean industries such as fishing, tourism and renewable energy contribute significantly to economic growth, they also present challenges in terms of wealth distribution and access to resources. Therefore, the concept of an inclusive economy is crucial for ensuring that ocean resources yield benefits and that such benefits are distributed in a fair manner across society, including persons in marginalized situations.

The Sustainable Development Goals contain a strong focus on the importance of gender equality in all aspects of sustainable development, including the governance of ocean resources. Integrating gender perspectives into ocean policies ensures that the needs, perspectives and rights of women are recognized and also ensures inclusive and effective management of marine resources (see subsect. 5B, chap. 6).

Gender-oriented policies and programmes that provide women with equal access to resources, decision-making power and economic opportunities are crucial for promoting both gender equality and the sustainability of ocean resources.

Ocean governance

- The recent adoption of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction marks a milestone in extending conservation and sustainable use of biodiversity into areas beyond national jurisdiction, reinforcing modern environmental standards and equitable benefit-sharing. The Agreement opens up a new pathway for internationally recognized area-based management tools, including MPAs for the high seas.
- However, the challenge continues to be the overcoming of institutional and thematic fragmentation, which would ensure that global, regional and national efforts are aligned under shared principles such as the ecosystem approach, the precautionary approach and the best available science.
- The third *World Ocean Assessment* is the first integrated ocean assessment to include an ocean governance section.
- The fragmentation of ocean governance at the global and regional levels has continued to draw significant attention over the past five years, and various mechanisms have been developed, including cross-sectoral interplay, systemic responses such as judicial proceedings, and other mechanisms that strengthen and foster multilevel cooperation such as in the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction.
- The application of ocean governance concepts across global and regional institutions strengthens legal connectivity, enhancing coherence and synergies in governance.

Ocean governance (see sect. 3) is underpinned by a highly complex and dynamic interplay of States, multilevel intergovernmental institutions and regimes, in which concepts, principles and means of implementation are developed and used.

The United Nations Convention on the Law of the Sea of 1982 sets out the legal framework within which all activities in the ocean and seas must be carried out.[3] Other global treaties have been progressively agreed in the past 70 years, including two agreements: the Agreement on Fisheries Subsidies, which entered into force in 2025, and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, which entered into force in 2026. These treaties address various aspects of the marine environment, including biodiversity protection, harmful fisheries subsidies, pollution from sectoral activities and other threats to the marine environment.

In addition, many non-binding instruments and associated intergovernmental policy processes are focused on the marine environment. These processes can facilitate cooperation, action and coordination among States (e.g. in the case of United Nations mechanisms such as UN-Oceans) or the development of a common scientific understanding (e.g. through the Intergovernmental Panel on Climate Change (IPCC), IPBES, the *World Ocean Assessment* and the United Nations Decade of Ocean Science for Sustainable Development).

However, the fragmentation of ocean governance at the global and regional levels has continued to draw significant attention since the publication of the second *World Ocean Assessment*. In recent years, new binding and non-binding instruments have been developed to strengthen the existing governance framework and address gaps in ocean governance, including mechanisms for cross-sectoral interplay (e.g. the Convention on Biological Diversity; the Kunming-Montreal Global Biodiversity Framework of 2022; the Agreement on Fisheries Subsidies of 2025; the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction of 2026; and the International Maritime Organization (IMO) greenhouse gas emissions strategy of 2023).

The application of ocean governance concepts across global and regional institutions strengthens legal connectivity, enhancing coherence and synergies in governance.

Over the past five years, the areas of concern of relevant intergovernmental institutions have expanded beyond traditional marine environmental issues (e.g. pollution and fisheries) to include more recent priorities such as climate change mitigation, plastic pollution, ocean monitoring and observation, food security, maritime security, migration by sea and human rights.

Overarching objectives such as sustainable and inclusive ocean economies, blue health and blue justice are playing a significant role in ocean governance, and the social sciences are becoming increasingly relevant in that regard.

[3] See the second *World Ocean Assessment*, at www.un.org/regularprocess/woa2, and General Assembly resolution 79/144.

5. Marine observations and ocean knowledge

Marine observations and technological developments advancing scientific understanding of the ocean

Effective ocean management, decision-making and policies must be based on observations, information and scientific knowledge acquired through an extensive and diverse array of methodologies and technologies used by multiple disciplines, including the social sciences. Technologies and methodologies for ocean observation are developing rapidly and, together with advances in modelling, they are greatly increasing the scientific understanding of the ocean and the development of management tools. These advances are partially responsible for the progress made since the publication of the second *World Ocean Assessment*. However, significant gaps remain when it comes to the knowledge of vast areas and important components of the ocean. There are also inequalities in access to data and technologies, as well as in scientific capacity across regions.

The use and development of automated or semi-automated ocean observation platforms, such as Argo floats (which are now being expanded to include deep Argo floats that observe depths below 2,000 m), gliders, submarine cables, unmanned autonomous vehicles, remote observing vehicles and drones, continue to expand. These platforms provide valuable data and information at an increasing range of spatial and temporal scales and resolutions below the ocean's surface. The observation of the ocean's surface was revolutionized decades ago by the use of satellites. However, the deeper domains of the ocean remain the subject of a major knowledge gap due to the challenges of observing deep waters, especially those far from the coast. This will be a major challenge during the implementation of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Nevertheless, significant progress has been made in identifying hotspots of biodiversity in deep-sea habitats, such as seamounts, submarine canyons, trenches and hydrothermal vents.

Newer observation platforms are equipped with higher-resolution and more precise sensors, as well as sensors that can measure new variables. Examples include the use of higher-resolution satellite sensors, the incorporation of biogeochemical variables into Argo floats, advances in image acquisition systems and the use of passive and active acoustic sensors in biological studies, including of fisheries. The critical importance of automated data acquisition systems was revealed when non-automated monitoring systems were interrupted during the COVID-19 pandemic.

However, the acquisition of real-time or near-real-time data is skewed towards physical variables rather than biological variables, with biochemical variables falling somewhere in between. This imbalance is due to the complexity of the biological components of marine ecosystems, the diverse nature of their variables (e.g. taxonomic, ecological and physiological), the lower number of sensors developed for biological variables and the energy consumption required for image acquisition systems and active acoustic sensors. Nevertheless, image acquisition systems and advances in acoustic technologies have significantly improved the understanding of biodiversity, species distribution patterns and fisheries management.

Nevertheless, research vessels are still essential platforms for studying the biogeochemical and biological components of the ocean, as well as for managing biological resources, such as fisheries, and for the conservation of biodiversity, habitats and ecosystems. In most cases, samples must still be processed in a laboratory.

The advancement and expansion of biomolecular technologies, such as genetic sequencing, in situ sequencing platforms, synthetic biology, metagenomics and environmental DNA/metabarcoding, have led to significant progress in biodiversity and ecology studies across all taxonomic groups, habitats, fisheries, aquaculture and MPA implementation and management. Nevertheless, the application of these techniques is limited. For example, the study of biodiversity still requires on-the-ground verification by expert taxonomists. Unfortunately, the number of taxonomists is decreasing globally, which has become a serious concern.

Furthermore, long-term monitoring and observation systems are needed to understand long-term ecosystem dynamics, including the effects of climate change, as well as for management and decision-making purposes. International initiatives such as the Argo programme and the Global Ocean Acidification Observing Network, which are coordinated under the Global Ocean Observing System, as well as more recent programmes under the Ocean Decade, continue to reinforce international cooperation and assist with the implementation and

standardization of methodologies and ocean indicators. However, long-term monitoring programmes are often hindered by a lack of adequate long-term funding.

Modelling is now widely used across all disciplines to study phenomena such as climate change, ocean circulation, species distribution, erosion and sedimentation, food web dynamics and fisheries and aquaculture. It contributes to progress in scientific understanding and serves as a management tool. The implementation of digital twins of the ocean and the application of artificial intelligence are particularly promising for management decisions. However, both digital twins and artificial intelligence require extensive data sets that adhere to the FAIR (findable, accessible, interoperable and reusable) principles. Although many data remain inaccessible, initiatives such as the European Marine Observation and Data Network, the Bureau of Ocean Energy Management, the Mid-Atlantic Ocean Data Portal and the International Oceanographic Data and Information Exchange are helping to meet the demand for data.

As discussed in section 3 on ocean governance (and further in sect. 4, chap. 1), effective decisions for the sustainable management of the ocean require the incorporation of social sciences. Therefore, ocean observation systems must integrate social variables, and social science must be increasingly incorporated into knowledge systems.

Indigenous, traditional owner and local community knowledge

- Indigenous, traditional owner and local community knowledge is increasingly being acknowledged as a valuable component of knowledge systems and ocean governance models. Effective knowledge systems are challenged by a persistent failure to recognize or engage with diverse world views, including Indigenous ways of knowing. Ocean governance models that incorporate Indigenous, traditional owner and local community knowledge are more likely to achieve comprehensive marine ecosystem and well-being outcomes.

"Indigenous, traditional owner and local community knowledge" collectively refers to knowledge systems developed by Indigenous Peoples, traditional communities and local communities through extended close interaction with their surrounding environment or long-standing continuous culture (see subsect. 5B, chap. 8, for an in-depth description). Indigenous, traditional owner and local community knowledge is increasingly being acknowledged as a source of information complementary to classical scientific information.

There is growing recognition that Indigenous, traditional owner and local community knowledge can provide insights valuable for sustainable resource management and biodiversity conservation. The loss of biodiversity and habitat not only is a significant ecological loss, but also leads to the loss of cultural identity. The cultural assets of most Indigenous, traditional and local communities are linked to the natural environment and significant changes in these environments can undermine the cultural security of these communities. The impacts of change (e.g. climate change) differ across societal and cultural groups and may vary greatly between Indigenous Peoples and non-Indigenous peoples. Certain social classes and groups will be affected differently from others. There has been a recognition of the need to meaningfully weave Indigenous, traditional owner and local community knowledge throughout the third *World Ocean Assessment* in order to capture a more holistic understanding of the state of the marine environment and inform sustainable ocean governance.

The ocean is an essential part of the planet's life-support system. Improving its health is crucial to the sustainability of marine ecosystems and the well-being of all life on Earth. Scientific understanding of the ocean must be advanced from an interdisciplinary perspective and across spatial and temporal scales if human activities and climate-related impacts are to be managed effectively.

Section 2
Approach to the *Assessment*

Key points

- The World Ocean Assessments are aimed at providing the best available, scientifically informed review of the state of the marine environment, including socioeconomic aspects, on a continual and systematic basis, through the development of regular targeted outputs that respond to policy needs, and by building capacity to support decision-making at all levels.
- Their development relies on the efforts of scientists and experts from around the globe, under the guidance of the States Members of the United Nations and with the support of the United Nations Secretariat.
- The collaborative process for the development of the third *World Ocean Assessment* involved regional workshops for scoping and drafting, followed by multiple rounds of review by peers, United Nations system organizations and Member States.
- In its resolution 79/144, the General Assembly reaffirmed the need for synergy among assessments from bodies and processes such as the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects, ensuring compatibility between global and regional evaluations.
- Some definitions and vocabulary required careful consideration during the development of the present *Assessment*.

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1. Introduction and background

The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects, is a multilevel initiative established after the World Summit on Sustainable Development of 2002. It is guided and overseen by an Ad Hoc Working Group of the Whole of the General Assembly, which was established in 2008.

The overall objective of the Regular Process, as set out by the Working Group in the proposed framework of the Regular Process (A/64/347, annex), is as follows:

> The regular process under the United Nations would be recognized as the global mechanism for reviewing the state of the marine environment, including socioeconomic aspects, on a continual and systematic basis by providing regular assessments at the global and supraregional levels and an integrated view of environmental, economic and social aspects. Such assessments would support informed decision-making and thus contribute to managing in a sustainable manner human activities that affect the oceans and seas, in accordance with international law, including the United Nations Convention on the Law of the Sea and other applicable international instruments and initiatives.

In its resolution 64/71, the General Assembly endorsed the recommendations adopted by the Ad Hoc Working Group of the Whole at its first meeting, including the recommendation that, in the first cycle, the scope of the Regular Process would be focused on establishing a baseline and that, in subsequent cycles, the scope would extend to evaluating trends (see A/64/347, annex, para. 19). In its resolution 75/239, the Assembly also endorsed the recommendations adopted by the Working Group at its thirteenth meeting, including the recommendation that, for the second cycle, the scope would extend to evaluating trends and identifying gaps (see A/75/362, annex, para. 2).

The third cycle of the Regular Process (2021–2025) is focused on three key outcomes: (a) assessments of the condition of the marine environment, including socioeconomic aspects; (b) support for and collaboration with other ocean-related intergovernmental processes, such as on producing a series of concise documents highlighting specific policy-relevant information from the second *World Ocean Assessment*; and (c) capacity-building, including a programme designed to enhance the capacity of States to strengthen the ocean science-policy interface at the national, regional and global levels.

Building on previous efforts, the programme of work in the period 2021–2025 for the third cycle of the Regular Process in relation to the development of the third *World Ocean Assessment* was focused on two specific major components (a sustainable and inclusive economy, and One Health), in addition to evaluating trends since the publication of the second *Assessment*, as guided by a scoping exercise.

The development of the *World Ocean Assessment* relied on the efforts of scientists and experts from around the globe, under the guidance of the States Members of the United Nations and with the support of the United Nations Secretariat.

To organize tasks associated with writing and review processes, various actors and parties connected with the Regular Process assumed different roles and performed tasks as contributors, institutional reviewers or other key participants in the Regular Process.

The Ad Hoc Working Group of the Whole, which oversees and guides the Regular Process, includes representatives of all States Members of the United Nations. The group has two Co-Chairs (one from a developing country and one from a developed country), who are appointed by the President of the General Assembly.

Between sessions of the Ad Hoc Working Group of the Whole, its Bureau ensures the implementation of its decisions. The Bureau consists of the Co-Chairs and representatives of 15 Member States – three appointed by each of the five regional groups in the General Assembly.

A Group of Experts was established with the general task of carrying out assessments under the Regular Process. It consists of up to 25 experts, representing the five regional groups. They structure outputs for the World Ocean Assessments and ensure that they are delivered on time following the available guidance and to the highest standards.

A mechanism to establish a pool of experts to assist the Group of Experts for the third cycle of the Regular Process (see A/76/391, annex I) was developed by the Bureau in accordance with General Assembly resolution 75/239. Without detracting from the other principles endorsed by the Assembly, the allocation of tasks to members of the pool of experts must reflect the principle of adherence to

equitable geographical representation in all activities of the Regular Process and have due regard to a desirable balance between genders.

Members of the writing teams for each output were drawn from the pool of experts and were responsible for writing the drafts of the outputs under the guidance of the Group of Experts. The members of the writing teams were selected on the basis of relevant expertise, with a view to ensuring regional representation and gender balance within the overall writing team.

In paragraph 347 of its resolution 77/248, the General Assembly noted the endorsement by the Ad Hoc Working Group of the Whole of the Guidelines for the Writing and Review Process of the next Assessment(s) of the Third Cycle, developed by the Group of Experts in accordance with the programme of work for the third cycle (see A/77/596, annex I, para. 3), in which the vision and mission of the third cycle were described as follows:

> **Vision**: for the *World Ocean Assessment* to become the key instrument to build environmental, economic and social resilience by informing decision makers of the challenges and opportunities for achieving a healthy ocean environment that supports sustainable development.
>
> **Mission**: to provide the best available, scientifically informed review of the state of the marine environment, including socioeconomic aspects, on a continual and systematic basis, through the development of regular targeted outputs that respond to policy needs, and by building capacity to support decision making at all levels.

According to the vision and mission statements, the main intended audience of the third *World Ocean Assessment* are people in all sectors who make decisions that will affect the marine environment. They cover a broad range of individuals and backgrounds, including, but not limited to, policymakers and legislators, scientists, business leaders and the general public.

2. Scoping the assessment

A first round of five regional workshops was held between July and December 2022, with a view to informing the scoping of the *World Ocean Assessment* and the development of an annotated outline for it, collecting regional-level data, raising awareness of the Regular Process and generating interest from the scientific community in contributing to the drafting of the *Assessment*.

The development of the third *World Ocean Assessment* was organized around three major steps: (a) scoping; (b) development of the outline; and (c) drafting and reviewing. Each of the steps is described in the present section. Interwoven within these steps were discussions on the frameworks and methodologies to be adopted, the strategies to be used to update the second *Assessment*, the expertise needed to produce the present *Assessment*, and the delivery methods to be employed.

Regional workshops played a critical role in the development of the *World Ocean Assessment*, from scoping through to drafting, by ensuring that the voices, knowledge and priorities of regional stakeholders were meaningfully integrated into the global assessment process. These workshops were designed as inclusive, highly participatory events that brought together representatives of Governments, academic institutions, civil society, Indigenous Peoples and local communities to co-create content that reflects regional realities and national specificities. By fostering open dialogue and knowledge exchange across diverse disciplinary, cultural and institutional perspectives, the workshops helped to ensure that the *Assessment* is grounded in both scientific evidence and lived experience.

Importantly, these regional engagements not only served to inform the assessment but also functioned as platforms for capacity-sharing and mutual learning, disseminating the work of the Regular Process, identifying and recruiting expertise for the writing teams and strengthening regional ownership and relevance of the final outputs. The success of the workshops, as well as the Ocean Future Scenarios and Pathways Workshop described below, relied heavily on the time, commitment and collaborative spirit of the participants. Their contributions have been essential to shaping an assessment that is globally coherent yet regionally nuanced, policy-relevant and actionable.

It should be noted that at this stage of development there was discussion as to whether the output would be produced as a single document or split into multiple assessments.

During the first round of workshops, participants were asked to consider various elements of the structure,

format and content of the assessment under the third cycle. The workshops were held in:

- United Republic of Tanzania, 25–27 July 2022, with a focus on the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea, the Gulf of Aden, and the Regional Organization for the Protection of the Marine Environment/Regional Commission for Fisheries area.
- Jamaica, 12–14 September 2022, with a focus on the North Pacific and the wider Caribbean area, convened by the International Seabed Authority (ISA).
- Argentina, 28–30 September 2022, with a focus on the South Atlantic (between the African and American coasts) and the wider Caribbean area.
- Kingdom of the Netherlands, 28–30 November 2022, with a focus on the North Atlantic, the Baltic Sea, the Mediterranean Sea and the Black Sea region.
- Indonesia, 13–15 December 2022, with a focus on the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea, the Gulf of Aden, the Regional Organization for the Protection of the Marine Environment/Regional Commission for Fisheries area, and the North and South Pacific.

Based on resounding feedback from the workshops, it was made clear that previous World Ocean Assessments were challenging in terms of accessibility, searchability and therefore utility. Many participants noted that they had not used the Assessments frequently due to these challenges. Participants recommended that the Group of Experts explore mechanisms to improve the ability of stakeholders to access the *Assessment*, find information in it and utilize that information. It was also pointed out that greater emphasis should be placed on the social components of the assessments.

The workshops also demonstrated that it would be of greater use to present information on pressures on the ocean and the human activities and responses to mitigate and manage those pressures in an integrated manner, rather than providing them as separate chapters. It was also stated that the social components of the assessments were underdeveloped and required greater emphasis. Likewise, although modified versions of the drivers-pressures-state-impacts-response framework had been adopted to differing degrees in the second *World Ocean Assessment*, influencing its overall design, it would be used in the third *Assessment*, when relevant, within individual chapters, thereby providing direct linkages between pressures, impacts and responses.

3. Outline of the assessment

Taking into account the extensive input from workshop participants, the Group of Experts undertook a series of in-depth brainstorming sessions to identify key elements from the workshops that would form part of the basis for the scope of the assessment.

To address the requests identified during the workshops, particularly to give greater prominence to the socioeconomic aspects of the third *World Ocean Assessment*, its main elements were organized around changes since the second *Assessment* (see sect. 4) and socioecological systems (sect. 5). Section 5 provides an integrated view of the social and ecological systems (coupled human-environment systems) of the ocean and the interactions between them. It is further divided into subsections on a sustainable and inclusive ocean economy (subsect. 5A) and One Health (subsect. 5B).

The period under review for changes since the second *World Ocean Assessment* was 2018–2023. Changes over longer time periods have been included where gaps were identified in the content of previous assessments.

During the brainstorming sessions, another prominent aspect was the request to feature potential responses to perceived challenges. As a result, sustainability pathways were incorporated into the outline of the third *World Ocean Assessment*. They include forward-looking feasible pathways, identifying the scientific data, tools and knowledge that could be utilized at the local, regional and global scales to ensure that human activities are sustainable and inclusive, while providing examples of where policy has been effective, including management approaches. The intention was not to prescribe specific uses of these data, tools and knowledge for specific sectors or situations, but rather to identify plausible evidence-informed future scenarios that incorporate the use of the data and knowledge currently available within the context of achieving the Sustainable Development Goals.

To address these requests, and in line with the vision of informing decision makers of the challenges and opportunities of achieving a healthy ocean environment that supports sustainable development, each chapter in the

subsection on the inclusive ocean economy (subsect. 5A) includes content relating to: (a) pressures; (b) sustainability pathways; and (c) socioeconomic components (benefits and disbenefits, equity, gender, and Indigenous, traditional owner and local community knowledge). Subsection 5B is organized within the framework of One Health, an integrated and unifying approach that sustainably balances and optimizes the health of people, animals and ecosystems. It recognizes that the health of humans, domestic and wild animals, plants and ecosystems is intrinsically linked while also being interdependent (One Health High-Level Expert Panel (OHHLEP), 2022). Subsection 5B has three main components: (a) the physical and chemical marine environment; (b) organisms that live in the marine environment; and (c) people. The One Health approach is recognized by the World Health Organization (WHO) as being particularly relevant to food and water safety, nutrition, zoonosis control, pollution management and antimicrobial resistance.

Among the other notable elements included for the first time in the third *World Ocean Assessment* are a new subchapter on fjord systems (sect. 4, subchap. 5R), a new section providing a global overview of ocean governance (sect. 3) and a new chapter on ocean hazards of natural origin (subsect. 5B, chap. 4). Subchapter 5N (Pelagic domain) of section 4 is an extension of chapter 7N of the second *Assessment* on the open ocean and covers epipelagic, mesopelagic and bathypelagic zones.

To address issues of utility, accessibility and searchability, it was decided that most of the third *World Ocean Assessment* would be produced in a web-based format that allows for digital linking between chapters and to core and external resources, including literature, graphics and supplemental material. The *Assessment* is available in the six official languages of the United Nations.

4. Drafting and review of the third *World Ocean Assessment*

To further develop the new and refocused elements of the scope of the *World Ocean Assessment*, a second round of five workshops was held between May and November 2023. These workshops were focused on the development of sustainability pathways for the chapters under subsection 5A (A sustainable and inclusive ocean economy) and the cross-cutting themes of equity, gender and Indigenous, traditional owner and local community knowledge in the chapters in subsection 5B (One Health), as well as on supporting the development of the social components addressed in each chapter of subsection 5A.

The workshops were held in:

- Santos, Brazil, 10–17 May 2023, for the South Atlantic (between the African and American coasts) and wider Caribbean region.
- Kingston, Jamaica, 12–16 June 2023, for the North and South Pacific regions and the wider Caribbean area, convened by ISA.
- Mahé, Seychelles, 30 July–4 August 2023, for the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea, the Gulf of Aden, and the Regional Organization for the Protection of the Marine Environment/Regional Commission for Fisheries area.
- Lisbon, Portugal, 25–27 September 2023, for the region of the North Atlantic, the Baltic Sea, the Mediterranean Sea and the Black Sea.
- New York, United States of America, 27–29 November 2023, for the region of the Indian Ocean (including the Arabian Sea and the Bay of Bengal), the Red Sea, the Gulf of Aden, and the Regional Organization for the Protection of the Marine Environment/Regional Commission for Fisheries area.

An Ocean Future Scenarios and Pathways Workshop in support of the third *World Ocean Assessment* took place in Berlin on 14 and 15 December 2023. It was organized by the German Marine Research Consortium together with the Leibniz Centre for Tropical Marine Research and with the support of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection of Germany. The aim of the workshop was to create a technically sound vision of sustainable oceans in 2050 and to highlight the most important characteristics. To make this possible, an interdisciplinary team worked for two days in three separate groups to sketch out what sustainable oceans could look like in 2050.

The outputs from these workshops were compiled and provided to the relevant writing teams for specific consideration and incorporation into the chapters and subchapters of section 5. Writing teams took varying approaches to considering and incorporating the outputs.

As the second round of workshops was being held, writing teams were assembled, starting with the selection of the coordinating authors. Once the coordinating authors had been identified, the Group of Experts worked with them to select the members of each writing team, striving to fill existing gaps. Pursuant to the Guidelines for the Nomination and Appointment of Experts to the Pool of Experts, Writing Teams and Peer Reviewers to Support the Works of the Third Cycle of the Regular Process (A/77/596, annex II), due regard was given to the principles of equitable regional representation and gender balance in the required expertise for all activities of the Regular Process. Further to the steps and procedures outlined in the mechanism for the establishment of the pool of experts for the third cycle of the Regular Process (A/76/391, annex I), additional guidance was provided for the recommendation of members of the pool of experts, with due consideration given to regional balance, gender balance, early-career professionals, traditional knowledge holders and non-academic stakeholders.

A meeting of coordinating authors was convened in Lisbon in February 2024 to facilitate the effective planning and coordination of the development of the third *World Ocean Assessment*.

An in-person meeting of Indigenous, traditional owner and local community knowledge experts, including Indigenous knowledge holders and scientists from diverse disciplinary and cultural backgrounds, took place in Paris in August 2024, allowing direct interaction for feedback on the draft chapter on Indigenous, traditional owner and local community knowledge. Multidisciplinary experts contributed to refining the chapter and providing guidance for its development.

Once the writing teams had completed their draft chapters, the drafts underwent review by the Group of Experts, a peer review and a preliminary evaluation by United Nations system organizations, followed by two rounds of review by States Members of the United Nations and United Nations system organizations.

This overall process involved the writing teams delivering a complete draft by November 2024. During most of that month, members of the Group of Experts reviewed the drafts, before they were revised by the coordinating authors and writing teams in December 2024. After further oversight by the Group of Experts, the zero draft of the third *World Ocean Assessment* was sent to external reviewers, including expert peer reviewers selected from the pool of experts and United Nations system entities. Comments were reviewed by the writing teams and subsequently considered by the Group of Experts, which consolidated them and approved draft 1.

Draft 1 of the third *World Ocean Assessment* was sent by the United Nations Secretariat to Member States, intergovernmental organizations and non-governmental organizations (NGOs) for review in May 2025, with a deadline of mid-June. The Group of Experts reviewed all of the roughly 1,300 responses prepared by the coordinating authors and writing teams in response to the comments received from States, intergovernmental organizations and NGOs on draft 1 and provided input on those responses when necessary.

Draft 2, resulting from the previous step, was sent to Member States, intergovernmental organizations and NGOs in mid-August 2025 for another round of review lasting until mid-September. Additional comments were addressed by the Group of Experts in consultation with the coordinating authors and writing teams when needed. This final review step concluded in October 2025.

It should be noted that chapters may have followed slightly different timelines to account for specific situations and challenges in the process.

The use of artificial intelligence in the development of chapters was limited to enhancing readability and language. Its use required human oversight, with all work carefully reviewed, ensuring that writing teams remained accountable for content integrity. Writing teams were required to disclose any use of artificial intelligence and cite the system used to generate text. Artificial intelligence-generated content could not replace critical tasks such as deriving scientific insights, conclusions or recommendations, in line with the principles for the ethical use of artificial intelligence in the United Nations system (CEB/2022/2/Add.1).

5. Definitions and vocabulary

Some definitions and vocabulary required careful consideration during the development of the third *World Ocean Assessment*, some of which influenced the organization and coordination of subjects in the various chapters. Some of the main examples are presented below.

Large-, medium- and small-scale fishing are defined and primarily addressed in subchapters 1A (Medium- and large-scale fishing) and 1B (Small-scale fishing, including subsistence fishing) of subsection 5A. They are distinct in their operations, each with unique practices, impacts and sustainability measures. Fisheries are classified by operational scale (FAO, Duke University and WorldFish, 2023), with large-scale and medium-scale fishing fulfilling different roles in the global fishing industry. Large-scale fishing is characterized by the use of large, high-capacity boats, often exceeding 130 m in length, with a hold capacity of more than 2,000 tons (FAO, 1985). Medium-scale fishing often occurs regionally with moderate-sized vessels (FAO, 1985). It serves as a bridge between artisanal fishing (or small-scale fishing) and large-scale fishing, adapting various fishing methods and technologies (Halimatussadiah and others, 2023). There is currently no globally agreed definition of small-scale fishing given that it can differ greatly in its operational characteristics and scale, making it challenging to identify and classify (FAO, Duke University and WorldFish, 2023). Nonetheless, some characteristics of small-scale fishing have been put forward, including being place-based and primarily for family consumption (low production), characterized by limited capital or resource inputs, but labour-intensive, and based on trips that are spatially and temporally limited (i.e. close to shore or completed within a day) (FAO, 2018). In addition, individual nation States have adopted a wide range of definitions linked to gear type (type and size of nets), length of boat and means of power, vessel ownership, trip duration and area of fishing activity (inshore, nearshore, etc.) (Pita and others, 2020; Smith and Basurto, 2019).

Small-, medium- and large-scale aquaculture are defined and primarily addressed in subchapters 1C (Medium- and large-scale aquaculture) and 1D (Small-scale aquaculture) of subsection 5A. There are no formal, globally accepted definitions to distinguish between small-, medium- and large-scale aquaculture, and scales can refer to different ranges in production, technology, economy, social factors, and environmental considerations and contexts (Krause and others, 2020). In the third *World Ocean Assessment*, medium- and large-scale aquaculture refer to commercially oriented production for domestic or export markets, conducted by companies ranging from medium-scale enterprises with employees at several farm sites to large-scale multinational companies with thousands of employees. Since no single, globally accepted definition of small-scale aquaculture is currently available, in subchapter 1D "small scale" refers to a single or clustered (community-based) farming unit involving relatively small production units, low investment, and limited technology and resources to raise aquatic organisms, often managed by individual farmers, their families and/or groups of farmers for local markets or as a supplementary livelihood.

The term "blue carbon" refers to the capture and long-term storage of carbon in certain marine habitats and its potential for climate change mitigation, and is defined in the IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC, 2022) as:

> All biologically-driven carbon fluxes and storage in marine systems that are amenable to management can be considered as blue carbon. Coastal blue carbon focuses on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. These ecosystems have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments. They provide many non-climatic benefits and can contribute to ecosystem-based adaptation. If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere. There is current debate regarding the application of the blue carbon concept to other coastal and non-coastal processes and ecosystems, including the open ocean.

The term was first applied to three coastal vegetated habitats – mangroves, seagrass meadows and salt marshes – that have high carbon stocks buried in their sediments, as measured by area. Later, the term was applied to other habitats, such as marine sediments, which store significant amounts of carbon due to their geographical extent despite low accumulation rates compared with coastal zones. More recently, other habitats such as kelp forests, despite having high rates of organic matter remineralization, have been suggested as blue carbon.

In the third *World Ocean Assessment*, the term "sustainable and inclusive ocean economy" is preferred over the term "blue economy", which it replaced whenever encountered in draft chapters during the writing process. The replacement circumvents the ambiguity derived from the multiple definitions adopted for "blue economy".[1] The concept of a "sustainable and inclusive ocean economy" recognizes that economic growth and environmental stewardship must go hand in hand with social and individual well-being. It encompasses how marine resources and the systems in place to govern them are used.

Nature-based solutions are defined in United Nations Environment Assembly resolution 5.5 as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits" (see UNEP/EA.5/Res.5).

The level of confidence assigned to findings is expressed using four main qualifiers that synthesize the writing teams' judgments about the validity of the finding, as determined by the evaluation of evidence and level of agreement. They are as follows:

(a) Inconclusive: representative of a suggestion or speculation with no or limited evidence. It is expected that this term will be used infrequently, but it provides writing teams with the opportunity to emphasize issues that are not established in science, but are important to policymakers or might have been highlighted by a different audience;

(b) Unresolved: representative of multiple existing independent studies in which the conclusions are not in agreement;

(c) Established but incomplete: representative of general agreement, but in a situation in which there are currently a limited number of studies and no comprehensive synthesis has been conducted, or existing studies imprecisely address the question;

(d) Well-established: where a comprehensive meta-analysis or other syntheses or multiple existing independent studies are in agreement. This represents multiple, consistent independent lines of high-quality evidence. Key findings may be further emphasized when there is high confidence in the use of the qualifier "very well-established" where there is a comprehensive evidence base and a very high level of agreement, or the qualifier "virtually certain" where the evidence consists of very robust data covering multiple temporal and spatial scales and there is almost no disagreement.

Acknowledgements

The third *World Ocean Assessment* has benefited from resources in the regular budget of the United Nations and would not have been possible without them. It also relied on the scientific output of the global scientific community, the result of the efforts of countless researchers and the investment of Governments and society in general from around the globe.

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Members of the Group of Experts and members of the pool of experts received no remuneration for their work.

[1] For instance, the World Bank PROBLUE programme defines a blue economy approach as the "sustainable use of ocean resources for economic growth, improved livelihoods, and job creation while preserving the health of ocean ecosystems" (see www.worldbank.org/en/programs/problue), whereas the European Union report on the blue economy of 2025 states, "The concept of the Blue Economy is multifaceted and often subject to varying interpretations. As a result, definitions differ significantly. One of the primary challenges in defining the Blue Economy is delineating its scope, as it encompasses a broad range of coastal, marine, and ocean-related activities with complex socio-economic benefits and environmental impacts". It presents a definition that does not include a sustainability dimension (see https://op.europa.eu/webpub/mare/eu-blue-economy-report-2025/general-overview/the-eu-blue-economy.html).

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Ollie Clarke

Section 3
Global overview of ocean governance

Key points

- Ocean governance is shaped by a complex and dynamic interplay of multilevel intergovernmental institutions, instruments and regimes in which concepts, principles and means of implementation are developed and adopted.
- The application of ocean governance concepts across global and regional institutions strengthens legal connectivity, enhancing coherence and synergies in governance.
- The multiplicity of ocean governance instruments at the global and regional levels has continued to draw significant attention over the past five years, thereby promoting the development of different mechanisms, including cross-sectoral interplay, requests for clarification through judicial proceedings and attempts to streamline governance such as in developing the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction.
- In the past five years, human dimensions, including human rights and social sciences, have gained increased prominence in ocean governance discussions.
- Governance concepts emerging from national experiences and non-State actors' proposals and practices, such as the sustainable and inclusive ocean economy and marine spatial planning, have gained increased significance in State-led governance developments.

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[1] The writing team is grateful for the comments and additional content provided by a large number of collaborators chosen because of their varied geographical origin and expertise in the various topics covered: Denis Bailly, Ana-Flávia Barros-Platiau, Robert Blasiak, Christian Bueger, David Alasdair Campbell Freestone, Thandiwe Gxaba, Quentin Hanich, Maria Teresa Infante, Nengye Liu, Robin Mahon, Philile Mbatha, Elisa Morgera, Andrei Polejack, Angelique Pouponneau, Violeta Radovich, Anais Remont and Karen Scott.

1. Introduction

The present section is the first dedicated section on ocean governance in a *World Ocean Assessment*, as in previous Assessments it was addressed within specific chapters, such as on fisheries. Earlier analyses of global ocean governance exist and were consulted (e.g. International Union for Conservation of Nature (IUCN), 1995; Mangalagiu and others, 2019). The present section first provides a brief overview of the institutional and legal architecture of ocean governance at the global and regional levels (see part 2 below) to which other substantive updates included in the Assessments relate, with a particular focus on developments in the past five years. This approach recognizes the central role played by States in shaping ocean governance concepts, principles and means of implementation, while also reflecting the influence of non-State actors regarding a more inclusive framework (e.g. Campbell and others, 2016; Niner and others, 2024). The analysis first examined 57 global treaties agreed between 1946 and 2024 that are applicable to marine protection and preservation. In addition to these treaties and their associated institutions, many non-binding intergovernmental processes have been central to the development of other elements and concepts of ocean governance at the global and regional levels, within and outside the United Nations system, that are included in the overview. Public-private and non-State processes can also be essential development nodes to form a polycentric (Mahon and Fanning, 2019; Naidoo and others, 2021) governance system (most recently Ostrom, 2010; see also subsect. 5A, subchap. 1C and chap. 8) and shape new governance narratives. These are included in part 2 of the present section, on the most prominent and fastest developing principles, concepts and means of implementation that underpin these global and regional polycentric ocean governance developments and provide the means to overcome institutional and sectoral fragmentation (see also sect. 4, chap. 1). To suit the non-exhaustive global and regional approach of the *World Ocean Assessment*, graphs and figures are used to demonstrate the complexity of the matter, including connections at different scales.

2. Developments and updates in global and regional institutional and legal mechanisms

The geographic scope and mandate of institutional and legal mechanisms can be global or regional, and they can also vary greatly in substantive scope. Interplays have been developed between institutions and instruments to overcome the adverse effects of fragmentation of the governance complex.

Global institutional and legal mechanisms

As the constitution for the ocean (Mann Borgese, 1975; Koh, 1983), the United Nations Convention on the Law of the Sea of 1982 (UNCLOS) (UNCLOS, 1982) plays a structural role in the global ocean governance framework (Boyle, 2005; see also Sustainable Development Goal target 14. c) and applies to all types of pollution of the marine environment and all activities at sea (UNCLOS, art. 194; International Tribunal for the Law of the Sea (ITLOS), 2024). Fifty-seven other global treaties (see table) have been agreed in the past 70 years (see figure I (a)), including two in the past five years, namely the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction of 2023 and the Agreement on Fisheries Subsidies of 2022. They are dedicated to different aspects of the marine environment, including biodiversity protection, pollution from sectoral activities and other threats to the marine environment, and are further complemented by numerous binding and non-binding instruments adopted by the many international frameworks whose mandates include the protection of the marine environment and its sustainable use (see figure I). Whereas some are restricted to the ocean, others also apply to the terrestrial environment (see table). The adoption of treaties by States, which has been steady overall with occasional peaks corresponding to the global or regional environmental political agenda at various times, has continued over the past five years (see figure I (c)). However, some treaties have been less widely adopted, potentially creating "free rider" situations, with some actors benefiting from the efforts of others (e.g. Barkin and Rashchupkina, 2017).

The implementation of international treaties and their further development for policymaking purposes are shaped and prioritized by a wide range of non-binding intergovernmental processes as well as arrangements with non-State actors. These processes can facilitate cooperation and coordination between States, United Nations entities and other relevant international bodies (e.g. International Criminal Police Organization

(INTERPOL) and United Nations mechanisms such as UN-Oceans) or the development of common scientific understanding (e.g. Intergovernmental Panel on Climate Change (IPCC), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), World Ocean Assessments and the United Nations Decade of Ocean Science for Sustainable Development). They also serve to identify and operationalize actions to address a given issue or even contribute to driving such actions at regional and national scales (e.g. Kunming-Montreal Global Biodiversity Framework of 2022; United Nations General Assembly (UNGA), 2019–2024; International Law Commission (ILC), 2024). They are further supported by international courts and tribunals that, for instance, provide guidance in the interpretation of relevant legal instruments, independently and as a whole (Tanaka, 2023a), and are instrumental or incremental in advancing the implementation of the Convention (Scott, 2023). Non-governmental processes and hybrid processes that involve States and non-State actors can also have an impact on the law-making or on the normative implementation (Mazzega and others, 2021; United Nations Department of Economic and Social Affairs, 2021).

Cross-cutting challenges have been central to dynamic policy developments in the past five years and a recurring reminder of the need for better means to overcome institutional and topical fragmentation in ocean governance developments. Most of the new binding and non-binding instruments were developed to strengthen the existing governance framework and address gaps in ocean governance accordingly, such as the Kunming-Montreal Global Biodiversity Framework of 2022, the Agreement on Fisheries Subsidies of 2022, the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction of 2023, and the International Maritime Organization (IMO) Strategy on Reduction of Greenhouse Gas Emissions from Ships of 2023 (Tanaka, 2023b; Kim, 2024). Several negotiations for new instruments in the past five years are ongoing, such as for an international legally binding instrument on plastic pollution, including in the marine environment (Brander and others, 2024), regulations on exploitations in the Area (Campanella, 2024; Blanchard and others, 2023) and amendments to IMO regulations to better address greenhouse gas emissions from shipping (Garcia and others, 2021; Chircop and Shan, 2020; see also subsect. 5A, chap. 6). Many issues that are the subject of increasing attention in ocean policymaking have also been brought before international courts and tribunals, including the overall coherence of the international legal order and human rights issues (ITLOS, 2024; International Court of Justice (ICJ), 2025; Independent Commission for Human Rights (ICHR), 2017; Nyman 2020; see also sect. 4, chap. 6).



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Table

Global treaties on the protection of the marine environment

GLOBAL TREATIES ON THE PROTECTION OF THE MARINE ENVIRONMENT

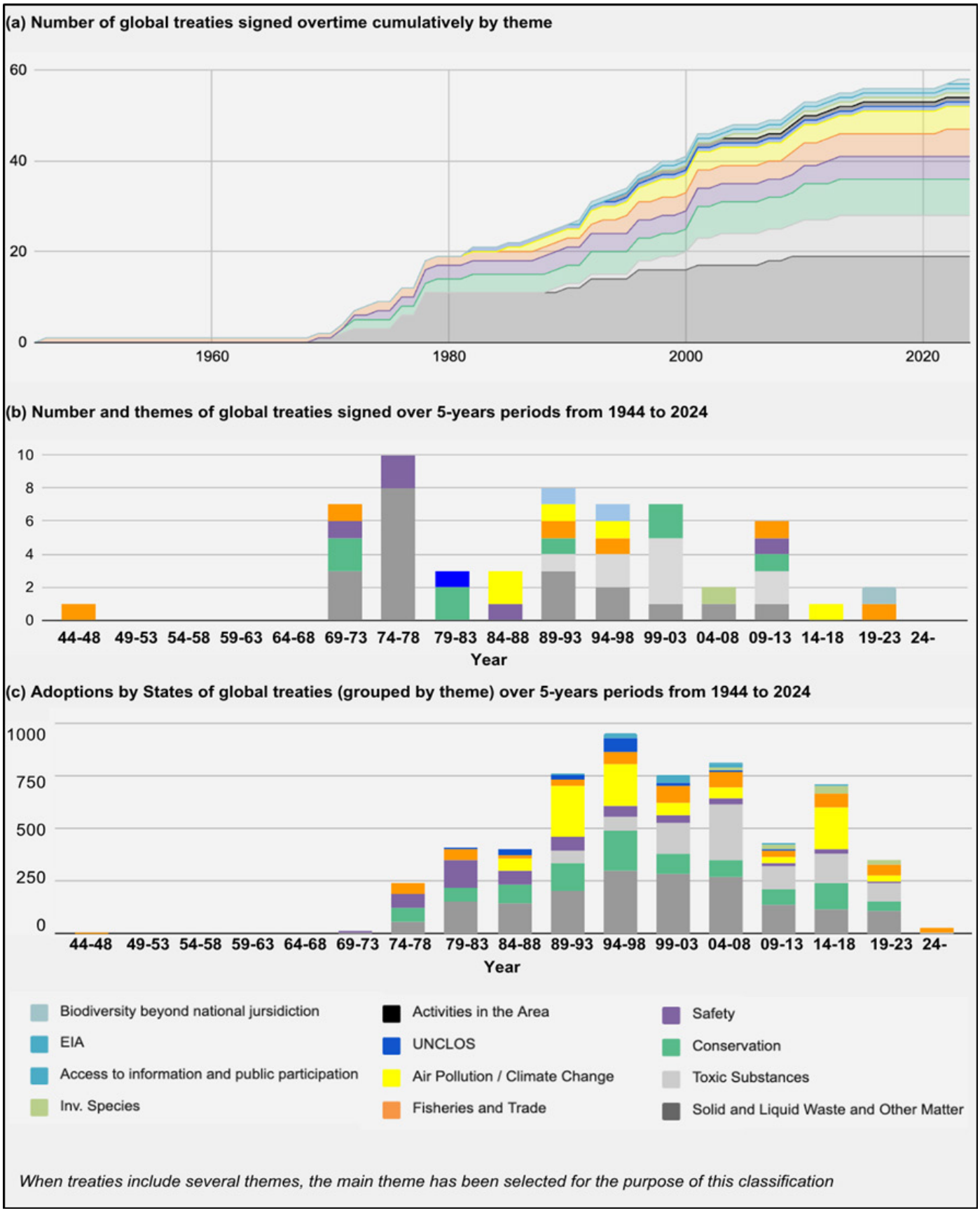
Includes all global treaties adopted since the Whaling Convention that relate to, or are directly relevant to the protection of the marine environment. It provides the date of signature of the treaty, its name, whether it applies primarily to the ocean environment (Y) or also applied to the terrestrial environment (N) and whether it has come into force (IF) or not (NYIF), has ceased (C) or is defunct (D)

Date	Treaty	Ocean sp.	Status
1946	International Convention for the Regulation of Whaling	Y	IF
1969	International Convention on Civil Liability for Oil Pollution Damage (CLC)	Y	IF
1971	Convention on Wetlands of International Importance (Ramsar Convention)	N	IF
1972	Convention Concerning the World Cultural and Natural Heritage (World Heritage Convention)	N	IF
1971	International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (FUND 1971)	Y	C
1972	Convention on the International Regulation for Preventing Collision at Sea (COLREGS) (as amended in 1981, 1987, 1989, 1993, 2001, 2007)	Y	IF
1972	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention)	Y	IF
1973	Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) / 1979 Bonn Amendment / 1983 Gaborone Amendment	N	IF
1974	International Convention for the Safety of Life at Sea (SOLAS)	Y	IF
1976	Convention on the Limitation of Liability for Maritime Claims (LLMC)	Y	IF
1976	Protocol relating to the 1969 International Convention on Civil Liability for Oil Pollution Damage (CLC PROT)	Y	D
1976	Protocol relating to the 1971 International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (PROT FUND 1971)	Y	C
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) and Annex I	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes II	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes III	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes IV	Y	IF
1978	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annexes V	Y	IF
1978	Protocol relating to the 1974 International Convention for the Safety of Life at Sea (SOLAS)	Y	IF
1979	Convention on the Conservation of Migratory Species of Wild Animals (CMS)	N	IF
1982	Paris Protocol relating to the 1971 Convention on Wetlands of International Importance (Ramsar Convention Prot)	N	IF
1982	UN Convention on the Law of the Sea (UNCLOS)	Y	IF
1985	Vienna Convention for the Protection of the Ozone Layer	N	IF
1987	Montreal Protocol on Substances that Deplete the Ozone Layer	N	IF
1988	Protocol relating to the 1974 International Convention for the Safety of Life at Sea (SOLAS PROT)	Y	IF
1989	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal / 1995 Amendment	N	IF
1990	International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC)	Y	IF
1991	Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention)	N	IF
1992	Convention on Biological Diversity (CBD)	N	IF
1992	Protocol relating to the 1969 International Convention on Civil Liability for Oil Pollution Damage (CLC PROT)	Y	IF
1992	1992 Protocol to Amend the International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1971 (IOPC-FUND)	Y	IF
1992	UN Framework Convention on Climate Change (UNFCCC)	N	IF
1993	Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas	Y	IF
1994	Agreement Relating to the Implementation of Part XI of the UNCLOS	Y	IF
1995	UN Agreement for the Implementation of the Provisions of the UNCLOS Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA)	Y	IF
1996	Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS)	Y	NYIF
1996	Protocol relating to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Prot)	Y	IF
1996	Protocol relating to the 1976 Convention on the Limitation of Liability for Maritime Claims (LLMC PROT)	Y	IF
1997	International Convention for the Prevention of Pollution from Ships (MARPOL) - Annex VI	Y	IF
1998	Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade	N	IF
1998	UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention) and its 2009 Kiev Protocol	N	IF
2000	Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC-HNS 2000)	Y	IF
2001	Agreement on the Conservation of Albatrosses and Petrels	Y	IF
2001	Convention on the Protection of the Underwater Cultural Heritage	Y	IF
2001	International Convention on Civil Liability for Bunker Oil Pollution Damage (Bunkers Convention)	Y	IF
2001	International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS)	Y	IF
2001	Stockholm Convention on Persistent Organic Pollutants (POPs)	N	IF
2003	Kyev Protocol on Pollutant Release and Transfer Registers	N	IF
2004	International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM)	Y	IF
2007	Nairobi International Convention on the Removal of Wrecks (Nairobi WRC)	Y	IF
2009	FAO Agreement on Port State Measures to Prevent, Deter and Eliminate IUU Fishing (PSMA)	Y	IF
2009	Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (SRC)	Y	IF
2010	Nagoya Protocol (Access and Benefit Sharing)	N	IF
2010	Protocol to the International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS PROT)	Y	NYIF
2012	Cape Town Agreement on Fishing Vessel Safety	Y	NYIF
2013	Minamata Convention on Mercury	N	IF
2015	Paris Agreement	N	IF
2022	Agreement on Fisheries Subsidies	Y	NYIF
2023	Agreement under the UNCLOS on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction	Y	NYIF

Source: Prepared by the writing team.

Figure I

Global treaties on the protection of the marine environment: signature and adoption by theme over time



Source: Prepared by the writing team.

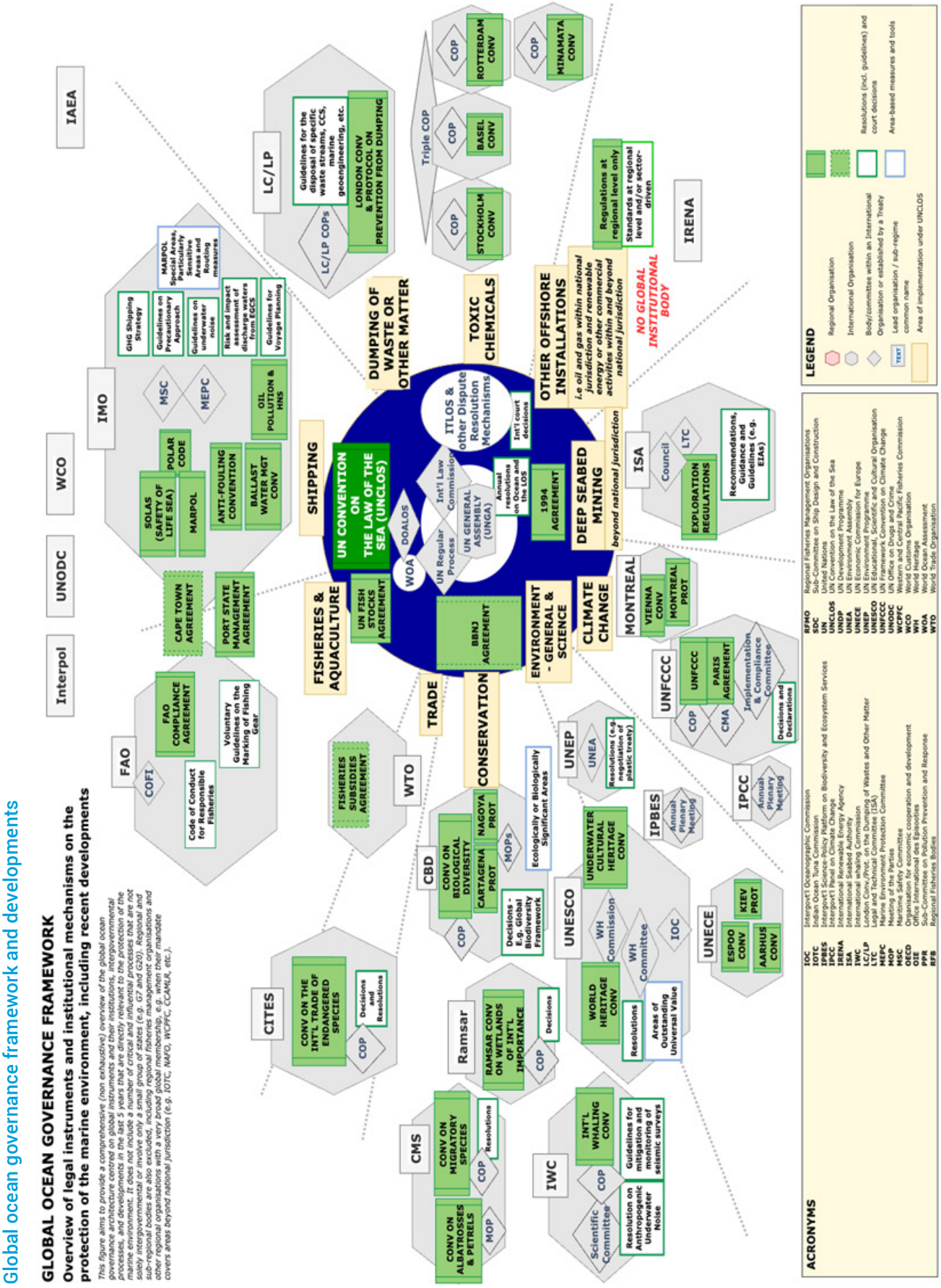
Regional institutional and legal instruments

Multipurpose organizations and arrangements focused on the protection of the marine environment form essential components of regional governance frameworks that complement global governance (Mahon and Fanning, 2019). As shown in figure II, these include 18 regional sea areas with mechanisms devoted to State coordination and the protection of the marine environment in maritime zones under their sovereignty and jurisdiction, and in some cases in areas beyond national jurisdiction (e.g. the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), the Convention for the Protection of the Natural Resources and Environment of the South Pacific Region (Noumea Convention) and the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR)). Six of the regional sea area mechanisms were established by and are still directly administered by the United Nations Environment Programme (UNEP) (Oral, 2015; UNEP, 2024). They are characterized by an interplay between several regional intergovernmental bodies, institutions and arrangements charged with different aspects of the coordination and management of the marine environment, as well as activities and research in the regional sea areas (Naidoo and others, 2021; Vince and others, 2017; Scheiber and Paik, 2013; Abdenur and Souza Neto, 2014). Foundational instruments often integrate definitions from the Convention, such as "pollution" and "dumping" in the Noumea Convention and the OSPAR Convention). Historical mechanisms have also often been strengthened, including by modernizing and updating older instruments such as General Assembly resolution 41/11 on fostering scientific research and environmental protection in the South Atlantic (Hatje and others, 2021). They continue to evolve through the adoption of new binding and non-binding instruments, including the Benguela Current Convention between the Government of the Republic of Angola and the Government of the Republic of Namibia and the Government of the Republic of South Africa (Benguela Convention) and the Mindelo Plan of Action, or are completed through crossover with other global and regional programmes, such as the IMO GloFouling project in the South Pacific. Additional arrangements have been agreed between subregional groups of States working on common ocean-related issues – including through economic integration arrangements such as Asia-Pacific Economic Cooperation – particularly on marine scientific research cooperation, such as the All-Atlantic Ocean Research and Innovation Alliance (Polejack and others, 2021), or to enhance cooperation with a view to protecting a particular area (e.g. the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention), the Mediterranean Strategy for Sustainable Development 2016–2025 and the Sargasso Sea Commission (see also sect. 4, subchap. 5Q)

Most regional seas frameworks operate through regularly revised strategic plans, managing numerous projects at varying scales (Vivero and others, 2023; Boukhari, 2019). The number, nature and scope of intergovernmental institutions and associated mechanisms vary, including in their degrees of delegation to external institutions or consultants (Al Ayachi, 2020). The scope of and level of detail in regional regulations and guidelines differ, with pollution sources and biodiversity being the most frequent topics in specific regional binding instruments (see figure II). Sectoral agreements and arrangements established by regional groupings complement these efforts (e.g. binding and non-binding management and conservation measures adopted by regional fisheries bodies, including marine protected areas (MPAs) under CCAMLR)). The protection of marine biodiversity, threatened species and habitats has been a focus since the late 1990s, as in the Pacific Regional Environment Programme strategic plan for 2017–2024 and the OSPAR North-East Atlantic Environment Strategy 2030, while renewed scrutiny on MPAs and other area-based management tools, including other effective area-based conservation measures, is very clear (e.g. the UNEP-Mediterranean Action Plan Medium-Term Strategy for 2022–2027 and efforts in the Ross Sea in the Southern Ocean in Antarctica (Brooks and others, 2021).

Over the past five years, key developments have been focused on marine plastic litter, biodiversity protection, assessment status and monitoring, including through the development of indicators (e.g. Coordinating Body on the Seas of East Asia, Baltic Marine Environment Protection Commission and OSPAR Regional Action Plan for Prevention and Management of Marine Litter in the North-East Atlantic (OSPAR Commission, 2014, 2022)). These developments can occur through the adoption of policy guidance and other non-binding documents, such as action plans, recommendations and guidelines, as well as new binding instruments, amendments to existing instruments or binding decisions of governing bodies if the regional regime allows, such as the OSPAR Regional Action Plan for Marine Birds.

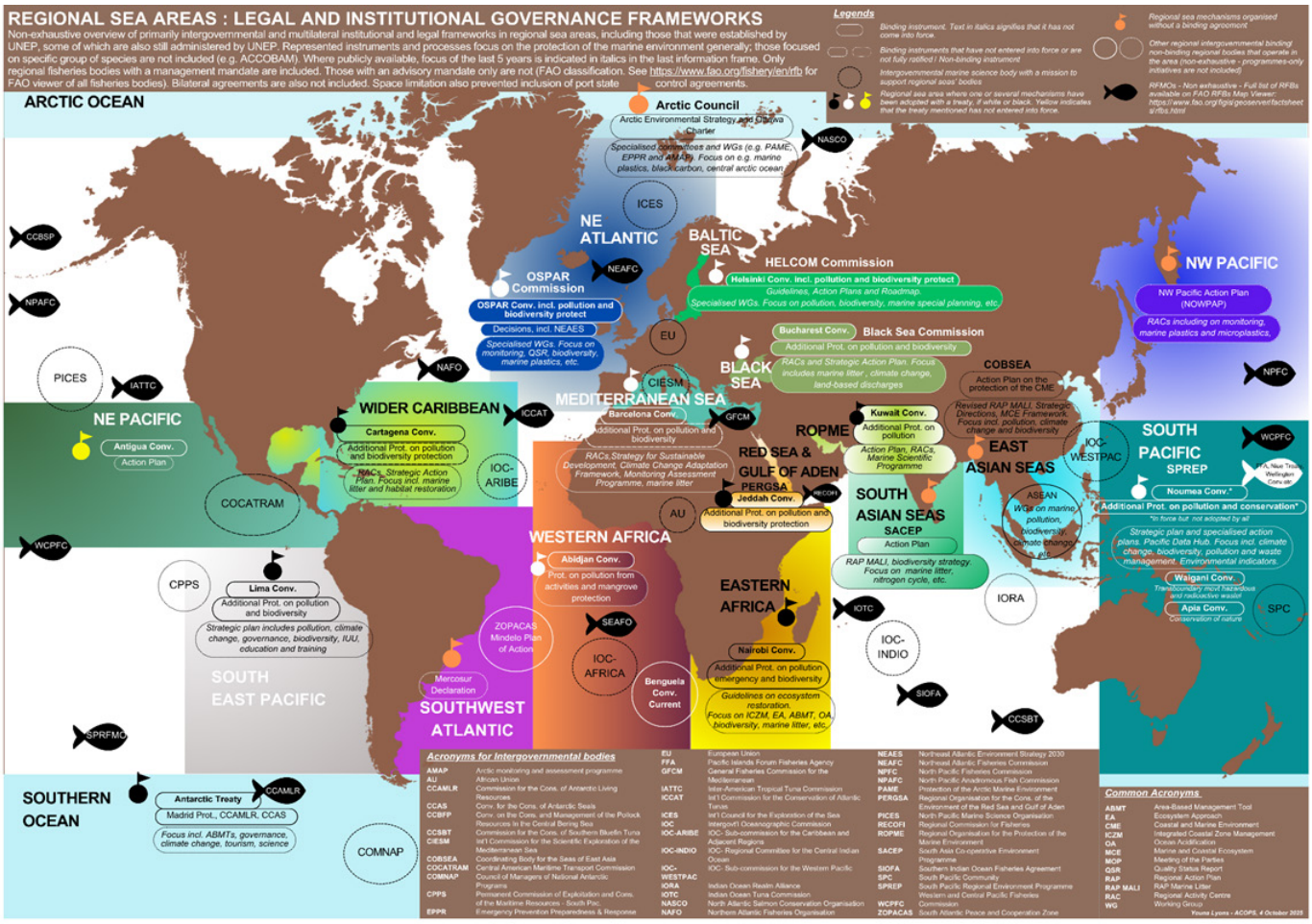
Figure II
Global ocean governance framework and developments



Source: Prepared by the writing team.

Figure III

Institutional and legal governance frameworks and developments in regional sea areas



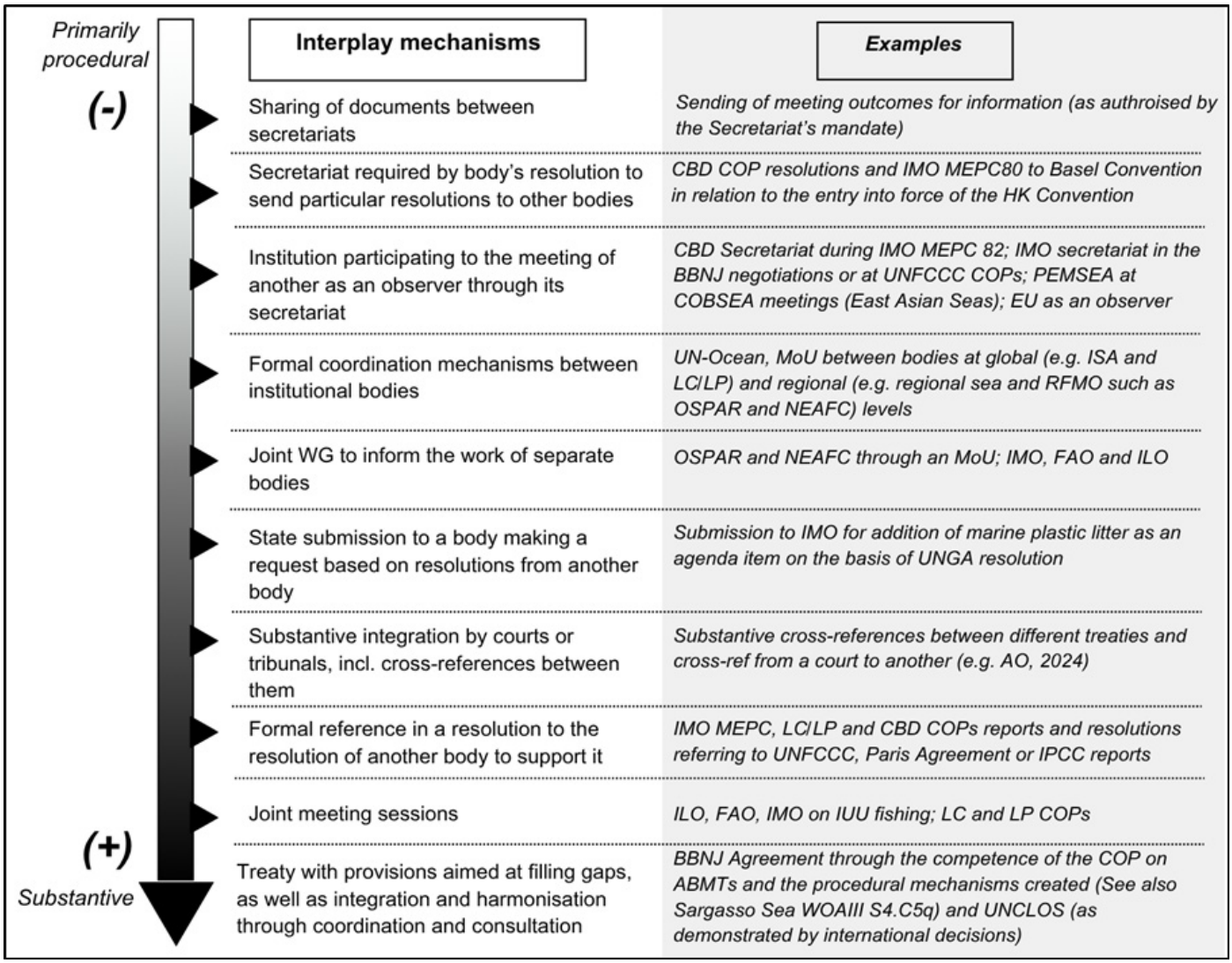
Source: Prepared by the writing team.

Interplay between institutions and processes

The multiplicity of institutions and instruments at different governance levels may be a challenge to the adoption and implementation of consistent, unified and complementary responses to marine environmental issues (e.g. Blasiak and Claudet, 2024, and Langlet and Vadrot, 2023, in the context of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction; and Fanning and Mahon, 2020). The multiplicity of mandates can also result in coordination difficulties, including the presence of gaps between mandates. Examples include the management of cumulative adverse effects from activities managed under different sectoral regimes and adequate responses to cross-cutting issues such as pollution from marine plastics, climate change and ocean acidification (Kim, 2012; Trevisanut and others, 2020; see also subsect. 5A, chap. 10; subsect. 5B, chap. 5; and sect. 4, chap. 6).

Political frameworks such as Sustainable Development Goal 14 (UNGA, 2015) and the Kunming-Montreal Global Biodiversity Framework of 2022 set objectives and provide specific targets and tools for marine environmental protection, helping to drive progress despite institutional and legal fragmentation (decision 16/35 of the Conference of the Parties to the Convention on Biological Diversity (CBD, 2025); and CBD, 2014). On a positive note, a number of other mechanisms and processes that facilitate interplay and interactions between institutions and regimes, as well as the adoption of complementary norms, can also be observed (see figure IV). In addition to procedural (formal and informal) interactions between subregimes, systemic integration approaches enable several substantive interaction mechanisms, both from within and from outside the ocean regime complex (Maljean-Dubois, 2022; see also, for example, sect. 4, chap. 6). These developments support and enhance overall coherence and synergies in ocean governance through their transversal operation.

Figure IV
Ocean governance legal and institutional interplay mechanisms



Source: Prepared by the writing team.

3. Transversal concepts, principles and means of implementation that underpin ocean governance

Ocean governance concepts, principles and means of implementation (hereinafter referred to as "concepts and approaches") have developed over time in different institutions of the ocean governance regime, sometimes in parallel and have gradually been incorporated into the overall ocean governance regime complex. Despite persistent uncertainties regarding their contours, legal nature and practical application (see figure V), such concepts and approaches are widely acknowledged to play a role in framing and shaping ocean governance, including in the influencing of negotiations, the interpretation of international and regional instruments and mechanism and the development of national law and policy.

Some concepts and approaches were expressly formulated at the global level in the United Nations Convention on the Law of the Sea. Many others were developed later in various texts such as declarations and guidelines that contribute to the implementation of the Convention, such as the Rio Declaration on Environment and Development of 1992, the Convention on Biological Diversity of 1992, the Food and Agriculture Organization of the United Nations (FAO) Code of Conduct for Responsible Fisheries of 1995 and the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Protocol) (VanderZwaag, 2019; Forteau, 2019; Zhang, 2021; Nakamura, 2023). Parallel narratives, shaped in part by non-State actors, can also play a central role in these processes, particularly in relation to the sustainable and inclusive ocean economy (Bennett and others, 2019; Germond-Duret and others, 2022), ocean health, blue justice (Bennett and others, 2021; Barros-Platiau and others, 2021; Jentoft and others, 2022) and maritime and food security (Bueger and Mallin, 2023; Suárez-de Vivero and others, 2019; Sun and others, 2024; see also subsect. 5A, subchaps. 1E and 1F; and subsect. 5B, chap. 2). Overall, these concepts and approaches can be of a procedural or substantive nature, involve scientific, social and economic sciences, and operationalize and reinforce an integrated approach.

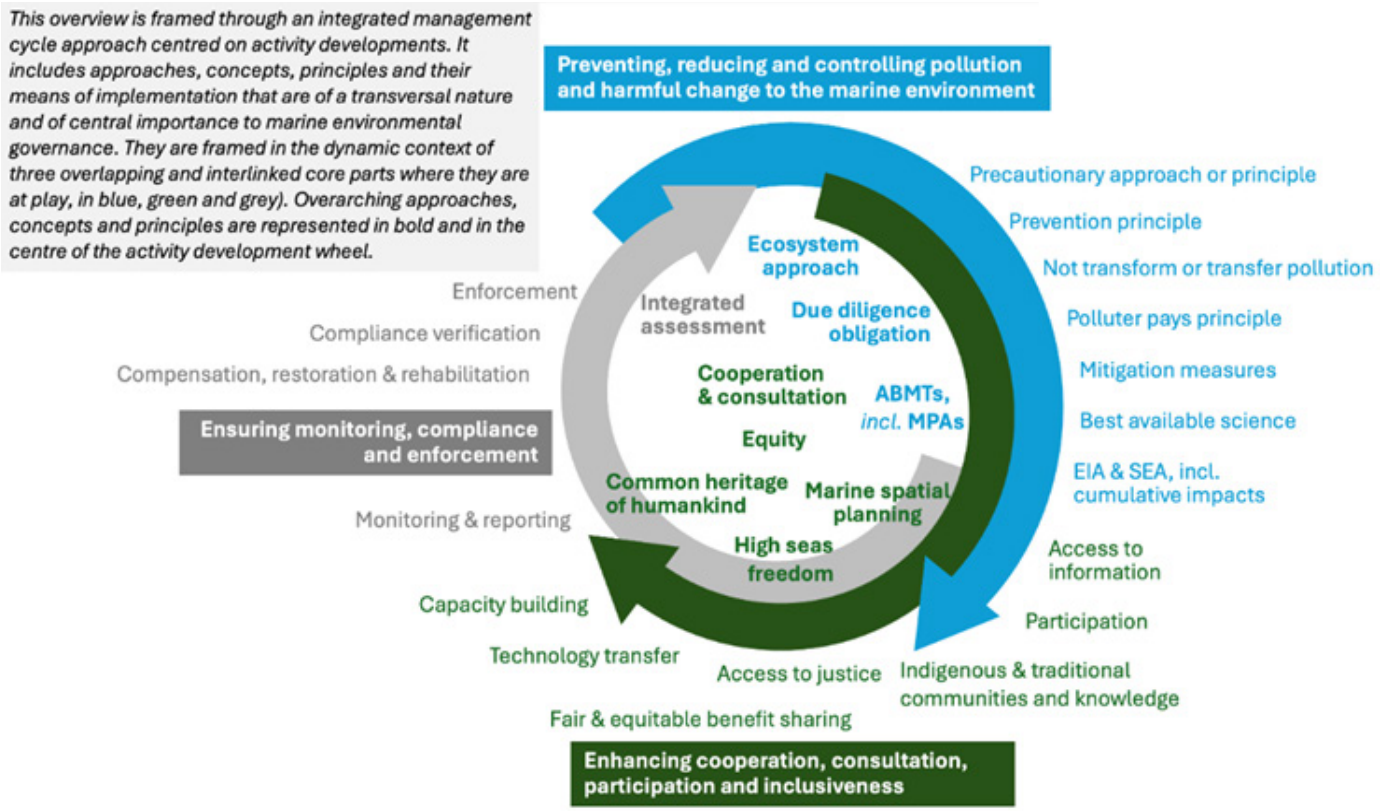
To highlight the significant overlap, articulation and circulation of these concepts and approaches, the present overview adopts a management cycle perspective, focusing on policy and activity developments over the past five years and three overlapping and interconnected drivers of marine environmental protection, presented under the headings below and illustrated in figure V. The figure is not intended to be an exhaustive representation of ocean governance.

Preventing, reducing and controlling pollution and harmful change in the marine environment

Implementation of the prevention, reduction and control of pollution of and harmful change to the marine environment (see United Nations Convention on the Law of the Sea, Part XII) brings into play several ocean governance concepts and approaches. The ecosystem approach is a central approach included in several legal instruments since its inclusion in CCAMLR in 1982 and its subsequent endorsement by the General Assembly in 2002 (Moynihan, 2022; De Lucia and Iavicoli, 2019; see also article 7 (f) of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction). It has evolved as an umbrella concept (see figure V) that articulates an integrated approach to ecosystem characteristics (e.g. scales and dynamics) and different sectors of activity (Long and others, 2015; Curtin and Prellezo, 2010; Nakamura, 2025; see also subsect. 5A, subchap. 1B) with regard to sustainable seas (ITLOS, 2024). Stand-alone approaches, concepts and principles that are also embedded in the ecosystem approach have been used extensively in support of global policy and regulatory developments in the past five years. Examples include the precautionary principle or approach (Rio Declaration, art. 15; United Nations Framework Convention on Climate Changes, art. 3; Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, art. 7 (e); Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, art. 6; London Protocol, art. 3.1; and FAO Code of Conduct for Responsible Fisheries, art. 6.5), the prevention principle (e.g. United Nations Convention on the Law of the Sea , art. 194; see also Duvic-Paoli, 2018), the obligation not to transform or transfer pollution (United Nations Convention on the Law of the Sea, art. 195; Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, art. 7 (l)), and mitigation measures that are taken to prevent, reduce or control harm to the marine environment and ecosystems (Vanderklift and others, 2022; see also, for example, sect. 4, subchaps. 4C and 4G, and subsect. 5A, subchap. 3A) from all sources, including climate change (Biermann and others, 2022).

Figure V

Ocean governance approaches, concepts, principles and their means of implementation for a sustainable and inclusive ocean economy, 2024



Source: Prepared by the writing team.

Applicable across all branches of international law, the due diligence obligation (French and Stephens, 2014; Besson, 2023) has also had its content consolidated by decisions of several international tribunals until very recently and in a range of contexts: deep seabed mining in areas beyond national jurisdiction (ITLOS, 2011), illegal, unreported and unregulated (IUU) fishing (ITLOS, 2015), climate change impacts (ITLOS, 2024), the aquatic environment (ICJ, 2010) and the marine environment in general (Permanent Court of Arbitration (PCA), 2016). Both customary (ICJ, 2010; Maljean-Dubois, 2021) and treaty-based (UNCLOS, 1982), the due diligence standard is recognized as varying with the risks involved – for example, depending on the sensitivity of an ecosystem or the risks from the activity being undertaken (e.g. ITLOS, 2024) – and to include, among other attributes, the use of the best available science and the fulfilment of environmental impact assessments. The need for the best available science is commonly referred to by ocean governance instruments and institutions, such as in Part XIII of the United Nations Convention on the Law of the Sea and in the OSPAR North-East Atlantic Environment Strategy 2030 (Polejack and others, 2021; see also subsect. 5A, chap. 7) and enabled by scientific bodies established by treaty bodies such as the Scientific and Technical Body under article 49 of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. The obligation to undertake environmental impact assessments to inform decision-making has long been a procedural obligation under customary international law (ICJ, 2010; Craik, 2007; ITLOS, 2024; see also Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, art. 7 (i)), as well as a direct obligation under article 206 of the United Nations Convention on the Law of the Sea, with other treaties providing particular substantive conditions in specific areas or sectors (e.g. Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol), art. 10; CCAMLR, art. IX; London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) of 1972, annex II; and Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, Part IV) (Doelle and Sander, 2020; see also subsect. 5A, chap. 7) and in areas beyond national jurisdiction (including cumulative

impacts, see Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, art. 1 (6)).

Global policy targets on protected areas (Sustainable Development Goal 14.5 and Kunming-Montreal Global Biodiversity Framework, sect. H, target 3) have driven global policy and regulatory developments for all area-based management tools broadly, including MPAs (Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, Part III). Amid a call for tighter regulations in order to effectively protect their marine environment (e.g. Grorud-Colvert and others, 2021; Claudet and others, 2024; Pike and others, 2024), regional seas organizations and mechanisms continue to adopt new instruments. The entry into force of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction is expected to further support this move, whether by stimulating the action of existing sectoral bodies or through the future adoption of new area-based management tools by the bodies to be established (Kim, 2024; see also International Seabed Authority (ISA), 2024).

Enhancing cooperation, consultation, participation and inclusiveness

The foundational principles of ocean governance, including the common heritage of humankind (formerly mankind), high seas freedoms, and cooperation and consultation among States, have been further elaborated and reinforced in the context of the development of more recent and interlinked marine environmental governance processes such as marine spatial planning, environmental impact assessments, strategic environmental assessments, area-based management tools, participation and inclusiveness (see figure V).

The status of the common heritage of humankind relates to the seabed, the ocean floor and the subsoil in the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, as well as the associated mineral resources (UNGA, 1970; see also United Nations Convention on the Law of the Sea, arts. 136 and 137; Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, art. 7 (b); and subsect. 5A, chap. 7). It is characterized by five essential attributes: non-appropriation (Convention, arts. 89 and 137), peaceful use (Convention, arts. 88 and 141), rational exploitation of resources (Convention, art. 150 (b)), international management, and equitable distribution of benefits (Kiss, 1983; Oliveira and others, 2025; UNGA, 1970; see also subsect. 5A, chap. 7). Some of these attributes, such as the peaceful use and rational exploitation of resources, are also applicable to high seas freedoms (Convention, art. 87; Agreement, art. 7 (c)).

The principle of equity has evolved under differentiated treatment (United Nations Convention on the Law of the Sea, arts. 202 and 203; Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, art. 7(d); see also subsect. 5B, chaps. 5 and 6) balanced by different provisions such as capacity-building and technology transfer (Convention, Part XIV; Agreement, Part V; see also Vierros and Harden-Davies, 2020). In this context, the fair and equitable sharing of benefits marks a normative clarification for marine genetic resources in areas beyond national jurisdiction that can be traced back to developments under the Convention on Biological Diversity, the International Treaty on Plant Genetic Resources for Food and Agriculture and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization to the Convention on Biological Diversity (Morgera, 2024; Batista, 2024; Blasiak and others, 2018; see also subsect. 5A, chap. 5). Another significant development is the explicit inclusion of the local, traditional and customary rights and knowledge of Indigenous Peoples, as well as of traditional and local communities that are knowledge holders on the ocean and coastal environments (Agreement, art. 7(j)), in, for example, scientific information (Harden-Davies and Gjerde, 2019; IPBES, 2022). Consultation of Indigenous Peoples and traditional knowledge holders has been progressively embedded into a number of processes, such as the Inuit Circumpolar Council becoming an observer to IMO (see IPBES, 2024; Golo and others, 2022; Rivers and others, 2023; Strand and others, 2022; Niner and others, 2024; see also subsect. 5A, chap. 9).

Cooperation is required in order to implement ocean governance measures and to settle disputes under, for example, articles 123, 169, 197 and 282 of the United Nations Convention on the Law of the Sea. It is given particular emphasis in the context of, for example, transboundary environmental issues (ITLOS, 2001, 2003), regional seas and due regard (PCA, 2016; Treves, 2019; Forteau, 2019). It is also associated with consultation, including the gathering of input from a wide range of relevant governance actors (Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, arts. 8 and 21; see also Kim, 2024 and Craik, 2020). Cooperation and meaningful consultation further support access to information, participation and access to justice, which are jointly described as “access rights” (e.g. Regional Agreement on

Access to Information, Public Participation and Justice in Environmental Matters in Latin America and the Caribbean (Escazú Agreement) of 2018, art. 2 (a)). Recognized in environmental treaty provisions that include transparency obligations (e.g. Convention, art. 119 (2); Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (Aarhus Convention), arts. 4 and 5; Escazú Agreement, arts. 5, 6, 7.1, 8.1 and 8.2; Kunming-Montreal Global Biodiversity Framework, target 21; Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, arts. 32 and 48) (see also Strand and others, 2022; Shields and others, 2023), these rights generally enable the protection (see also subsect. 5A, chap. 9) and exercise of various human rights related to a healthy environment (see also subsect. 5B, chaps. 2 and 3) and the fulfilment of the duty to protect, preserve and restore the environment (Morgera, 2024; see also Preamble to the Aarhus Convention).

Cooperation and consultation are also central to marine spatial planning. Although other forms of planning exist, marine spatial planning is generally a planning tool of reference across international (e.g. United Nations Educational, Scientific and Cultural Organization Intergovernmental Oceanographic Commission (UNESCO-IOC), 2021), regional (e.g. European Union directive on marine spatial planning, OSPAR and Baltic Marine Environment Protection Commission) and national ocean governance developments (Gerhardinger and others, 2019; Johnson and others, 2020; Stockbridge and Kuempe, 2024). It was first envisaged to resolve marine and maritime use conflicts in particular marine areas under national jurisdiction (Ehler and Douvere, 2009), and has since evolved (UNESCO-IOC, 2021, 2024) as an integrated approach that can anticipate conservation in ecologically sensitive areas and secure investments for economic development (Douvere, 2008), connecting stakeholders and supporting decision-making for marine use management (see subsect. 5A, subchaps. 1B, 1C and 1D), including in transboundary contexts (Gomes-Ballesteros and others, 2021; see also subsect. 5A, chap. 9).

Enhancing monitoring, compliance and enforcement

Integrated assessments are overarching governance tools to ensure the monitoring, compensation, compliance and enforcement provided for in numerous international instruments with a view to ensuring effective protection and preservation of the marine environment (Cicin-Sain and others, 1998). Reporting (e.g. Convention on Biological Diversity, art. 26; London Protocol, art. 9) and monitoring (e.g United Nations Convention on the Law of the Sea, art. 204; OSPAR, art. 6; London Protocol, annex II; Convention for Cooperation in the Protection and Sustainable Development of the Marine and Coastal Environment of the Northeast Pacific (Antigua Convention) of 2002, art. 3 (h); Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention), art. 6 (2) (e); Convention on Biological Diversity, art. 7) are typically focused on the periodic measurement of environmental quality indicators or targets at different spatial and temporal scales to detect and document the potential changes and impact of human activities (Han and others, 2020), including with respect to specific sea areas, ecosystems and species. Marine environmental data collection, including traditional knowledge (Kumar and others, 2021), has been improving at the global level, as demonstrated by the present *World Ocean Assessment*, UNESCO-IOC (2024), other reports on specific aspects such as marine transport (by the United Nations Conference on Trade and Development (UNCTAD)), fisheries (FAO and regional fisheries management organizations (RFMOs) (see also sect. 4, subchap. 4D); Rindorf and others, 2017; Stephenson and others, 2017) and the contribution of nature to people including ecosystem services (IPBES, 2019), although it remains largely insufficient, such as for invasive species (sect. 4, chap. 6), liquids, and solid and atmospheric inputs from land-based sources (sect. 4, chap. 6) and more generally (sect. 4, chap. 2). At the regional level, examples of knowledge improvement include quality status reporting under OSPAR in the North-East Atlantic (OSPAR Convention, art. 6) and under the Barcelona Convention in the Mediterranean Sea (Barcelona Convention, art. 12).

Monitoring and reporting also provide useful baselines for marine environmental compensation and restoration (ITLOS, 2024; Mendis, 2022). Compensation can provide redress or remediation through financial or material solutions (e.g. habitat restoration) when environmental damage to people or nature cannot be fully avoided or mitigated and rests on the "polluter pays" principle (López-Portillo and others, 2017). Restoration and rehabilitation (ITLOS, 2024; see also the Kunming-Montreal Global Biodiversity Framework) can involve public and private actors (Ramírez-Monsalve and others, 2021) in order to return damaged ecosystems to their original state or to support ecosystem recovery and promote resilience from future harmful impacts (Van Tatenhove and others, 2021; Bayraktarov and others, 2016).

The growing focus on compliance (von Stein, 2013, as cited in Lutmar and Carniero, 2018) and enforcement (Lutmar and Carniero, 2018) encompasses illegal activities (Warikandwa, 2023; Kuemlangam and others, 2023; FAO, 2021, 2022; INTERPOL, 2024; Lancaster and Erinosho, 2023; McCarthy and others, 2024; United Nations Office on Drugs and Crime (UNODC), 2024; see also subsect. 5A, subchap. 1A). Maritime security challenges can cause devastating environmental damage in addition to human and economic losses (Ho, 2006), such as the explosion of a supertanker to block key straits or the destruction of undersea pipelines, releasing toxic substances (Sondakh, 2006; Richardson, 2004). Responses to these threats have included the adoption of standards by intergovernmental organizations such as the World Customs Organization (WCO) SAFE Framework of Standards to Secure and Facilitate Global Trade, as well as capacity-building (e.g. WCO and secretariat of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade and the Stockholm Convention on Persistent Organic Pollutants; UNODC, 2023).

4. Conclusion

Over the past five years, substantive areas of concern in the work of relevant intergovernmental institutions have extended beyond traditional marine environmental pressures (e.g. pollution and fisheries) to more recent priorities (e.g. climate change mitigation and adaptation, marine plastics, monitoring and ocean observation) and non-traditional areas such as maritime security, migration by sea, a human rights-based approach and food security. Overarching objectives such as a sustainable and inclusive ocean economy, ocean health and blue justice are playing central roles in ocean governance developments.

The ocean governance overview provided in the present section highlights the central role of both natural and social sciences, including the knowledge systems of Indigenous Peoples and local communities and the importance of their integration into all stages of the policy cycle at all geographic scales.



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Section 4 Changes since the second *World Ocean Assessment*

Section 4 of the third *World Ocean Assessment* is focused on providing details of the changes that have occurred in the ocean since the period covered by the second *Assessment*, between 2018 and 2023, relating directly to the corresponding chapters in the second *Assessment*. All relevant information is described with respect to various geographical ocean regions.

Chapter 1 (Drivers) of section 4 provides a list of drivers updated since the second *World Ocean Assessment*. Chapter 2 (Scientific understanding) is focused on improvements and advancements in ocean science and technology, including various human-ocean interactions and relationships. Chapters 3 (Trends in the physical and chemical state of the ocean), 4 (Biodiversity) and 5 (Habitats) provide updates since the second *Assessment*. A subchapter on cephalopods has been incorporated into chapter 4 and a subchapter on fjord systems has been added to chapter 5. Furthermore, the subchapter entitled "Open ocean" in the second *Assessment* has been replaced by the subchapter "Pelagic domain", which also includes shelf areas. Chapter 6 (Pressures) provides a cross-cutting analysis of changes in pressures, such as erosion and sedimentation, and cumulative effects.

Chapter 1
Drivers



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1. Introduction

The adverse effects of human activities in the marine environment require a conceptual understanding of a cause-consequence-response framework based on knowing the basic human needs related by the environment, the activities required to satisfy those needs and the pressures (mechanisms of change) emanating from those activities (Elliott and Kennish, 2024). This encompasses both natural and human realms and frameworks (i.e. the socioecological-environmental system) to better understand how changes are manifested (Bograd and others, 2019; Smith and others, 2025). The prevention and mitigation of actual or potential adverse changes require effective governance and management.

Marine-based human activity sectors include physical restructuring of catchments, coastlines and the seabed; extraction of non-living and living resources; energy production; cultivation of living resources; transport, urbanization and industrial uses; tourism and leisure; and security and defence. An additional sector relating to nature conservation, protection and restoration may be included.[1]

Drivers are widely regarded – including by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the Intergovernmental Panel on Climate Change (IPCC), the European Environment Agency and regional seas conventions – as any natural or human-induced factor that directly or indirectly changes the ecosystem (Millennium Ecosystem Assessment, 2003; Haines-Young and Potschin, 2018; IPBES, 2024; Elliott and Kennish, 2024; Balvanera and others, 2019, 2020; Díaz and others, 2018; Hill and others, 2021; European Environment Agency, 2019; Blanco and others, 2014). In the present chapter, the human drivers having the greatest influence on the marine environment and its sustainability are:

(a) Population growth and demographic changes, and demand for resources (e.g. food, space or energy);

(b) Economic activity, as both the cause of and reasons for many of the activities leading to the pressures on natural and social systems;

(c) Technological advances, as activities that may create both beneficial and adverse consequences;

(d) Changing governance structures and social, economic and geopolitical instability: these are both the responses (as management measures) and results of demand for resources;

(e) Climate change, biodiversity loss and pollution resulting from the activities and effects of an increasing population and its demands for goods and benefits, and their production, transport and ability to fulfil basic human needs (e.g. food, security, employment and recreation). The resulting pressures include an increase in atmospheric greenhouse gases, as well as contamination leading to pollution as an adverse effect on all levels of biological organization. The drivers are also influenced by demographic changes in the form of climate migrants.

2. Drivers of change in the marine environment

Population growth and demographic changes

Although the global human population increased from 7 billion in 2011 to 8.2 billion in late 2024,[2] the growth rate has decreased, from 2.1% in 1968 to 0.87% in 2024, but the global population is nevertheless projected to reach 9.7 billion by 2050. The decrease in the growth rate results from a declining birth rate, especially in the global North, with lower mortality rates and an increased lifespan resulting from improved health. This is accompanied by the increasing average age of the global population.[3]

An estimated 37% of the global population, or 3.03 billion people, live within 100 km of the coast, twice the overall average population density (Cosby and others, 2024). Around 11%, or approximately 900 million people, live on land that is less than 10 m above sea level, known as the low-elevation coastal zone (Barbier, 2015), and this is projected to rise to more than 1 billion by 2050.

Increasing urbanization and industrialization, including exploitation, are among the most important trends in the coastal area. They also increase pressure on river

1 See https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/qsr2023-reference.
2 See https://ourworldindata.org/economic-growth.
3 See https://population.un.org/wpp.

catchments given the increased use of resources (water, food, physical resources and space), and greater transport and energy use. This leads to the need to remove waste or for uncontrolled discharge of waste (see sect. 4, chap. 6).

Economic activity

Economic activity, measured as gross domestic product (GDP) per capita, has grown steadily globally, with very high geographical variability, although manufacturing has decreased and services have increased in specific areas. Growth has slowed as a result of a declining trade volume, especially in light of global shocks.

Given that 41–45% of global economic activities are concentrated along the coast (Patterson and Glavovic, 2013), increased coastal urbanization and industrialization have enhanced demand for societal goods and benefits, including energy and other resources, and led to changes in tourism and recreation. This in turn has expanded the use of natural resources through extraction, production, consumption and waste generation. This may be termed the increasing industrialization of the seas.

Total energy demand, measured in million tons of oil equivalent (Mtoe), grew from 13,267 Mtoe in 2014 to 13,978 Mtoe in 2018.[4] Global energy consumption accelerated in 2023 by 2.2%, which was faster than its average growth rate of 1.5% per year from 2010 to 2019.[5] At the same time, primary energy intensity, which reflects energy use in the global economy, declined to 0.8% in 2021 from an average of 1.8% in the previous decade.[6]

The reduction in GDP generated per unit of energy used is the result of several short-term factors, such as the reduction in fossil fuel-based electricity generation, together with an increase in less energy-intensive industries. Many countries have reduced fossil fuel use, especially with the closure of coal-fired power plants, while renewable energies have expanded. Improved technologies have increased marine-based renewables, especially offshore wind power, although other marine energy technologies, such as wave and current turbines, are at the prototype stage, with usage increasing. In 2023, the global operational capacity for marine renewable energy reached 527 MW, while the cumulative capacity was 67.8 MW for emerging ocean technologies, 41.4 MW for tidal stream energy and 26.4 MW for wave energy[7] (see subsect. 5A, chap. 3). In 2023, mature marine energy generation technologies enabled 8.8 GW of new installations, bringing total global offshore wind power capacity to 64.3 GW. This reflected an annual growth rate of 16%, representing 7% of global energy production.[8]

The economic benefits of extracting marine biological resources (fish, shellfish and algae) are increasing as the coastal population grows. Mariculture is increasing and starting to move offshore to floating cages as well as having an inshore and estuarine or fjordic culture. Marine capture fisheries production has remained relatively stable in the past three decades, but the sustainability of fisheries resources is of concern.[9] According to the latest assessment of the state of marine fishery resources by the Food and Agriculture Organization of the United Nations (FAO), 64.5% of fish stocks are considered to be biologically sustainable.[10] Wild fishing and mariculture activities have an impact through overfishing, by-catch (the accidental taking of unwanted species and sizes), habitat loss and the transfer of pests and diseases (Haas and others, 2020) (see subsect. 5A, chap. 1).

There are continuing demands for and increases in the extraction of nearshore coastal and marine aggregates and minerals; sand and gravel mining is mostly inshore for construction and beach nourishment and, from 2012 to 2019, there was an increase in sand extraction, with 4 billion to 8 billion tons extracted annually (see subsect. 5A, chap. 7).[11] In addition, the exploration potential for offshore deep mineral mining has led to proposals for mining deeper resources of ferromanganese crusts, manganese nodules, seafloor sulfides, phosphorites and phosphates, and even marine diamond mining.[12]

Marine biotechnology is an emerging global industry for food and feed, cosmetics, aquaculture, agriculture

4 See https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html.
5 Ibid.
6 See www.iea.org/reports/sdg7-data-and-projections/energy-intensity.
7 See www.oceanenergy-europe.eu/wp-content/uploads/2023/03/Ocean-Energy-Key-Trends-and-Statistics-2022.pdf.
8 See www.gwec.net.
9 See https://openknowledge.fao.org/items/8ab20ccf-1e9d-4ae6-836c-ca770d16da01.
10 See https://openknowledge.fao.org/items/8bf1f881-9208-4c59-86e2-9ada635960dd.
11 See www.unep.org/news-and-stories/press-release/unep-marine-sand-watch-reveals-massive-extraction-worlds-oceans.
12 See www.usgs.gov/centers/pcmsc/science/global-seabed-mineral-resources.

and chemicals, diversifying into industrial enzymes, functional foods, cosmeceuticals, pharmaceuticals, biomaterials, bioprocessing and medical devices. The global market for such products and processes was predicted to reach $6.4 billion by 2025 (European Marine Board (EMB), 2017). The 10 largest companies in eight core ocean economy industries generate, on average, 45% of each industry's total revenue, and the 100 largest corporations account for 60% of total revenue (Virdin and others, 2021).

The coronavirus disease (COVID-19) pandemic greatly affected social, economic and environmental ocean aspects. Social lockdowns and travel restrictions decreased tourism and recreation in coastal areas, altering community dynamics that rely on ocean access for leisure and livelihoods (United Nations Educational, Scientific and Cultural Organization (UNESCO), 2021; Bennett and others, 2020). Economically, many fishing and tourism-dependent industries and communities faced significant losses due to reduced demand and operational challenges, increasing unemployment and financial insecurity (FAO, 2020; International Maritime Organization (IMO), 2020). Environmentally, reduced human activity in the short term improved water quality, decreased marine pollution and human impacts and improved biodiversity. However, the long-term consequences of increased discarded plastic waste from medical supplies and single-use items pose new challenges (Zhang and others, 2020; Cozzoli and others, 2020; Harrison, 2020). While the pandemic highlighted the need for sustainable practices, it also emphasized the vulnerability of ocean-dependent communities and ecosystems.

Technological advances

The growth of sustainable inclusive ocean economies, increasing urbanization and increasing industrialization on land and at sea have been accompanied by marine technological advances, each with their own activity, pressures and effects footprints (Elliott and Kennish, 2024). For example, fisheries technologies have both increased catches and helped to reduce by-catch. There have been technological advances in monitoring, surveillance and catch reporting, and in the use of artificial intelligence and environmental DNA in fisheries litter reduction and in seabed scanning in relation to habitat change and resource extraction (e.g. seabed mining). Improved monitoring and control of fishing, including the use of automatic identification systems and vessel monitoring systems, is aimed at reducing illegal, unreported and unregulated (IUU) fishing, as required in the context of Sustainable Development Goal 14 (Andriamahefazafy and others, 2022).

On land, urban and industrial energy production and use have changed through technological innovation, leading to greenhouse gas reductions. However, such reductions are not uniform nationally, regionally and globally.

Changing governance structures and geopolitical instability

Governance is the framework by which an entity (country, company or organization) is directed and controlled. At a country level it encompasses policies, political action (including parliamentary action), public administration and legislation. Plans and programmes should then aim to implement these policies by means of technical measures (Cormier and others, 2022; Glavovic, 2024). Governance is broader than, but an integral part of, management in that it governs the political, economic and societal realms. Marine management operationalizes governance by encompassing the public and private realms, with Governments implementing policies, resulting in laws, which then require rules and regulations (Glavovic, 2024; Elliott and others, 2025). Marine industries in turn adopt operational aspects to support economically and societally successful and sustainable businesses. Governance should be vertically integrated, from the local to the global level and vice versa, and horizontally integrated across sectors. In turn, each legal instrument requires an administrative competent body, usually at the national level, for implementation, again resulting in each country having a plethora of often overlapping statutory bodies (see sect. 3).

Global initiatives are underpinned by regional agreements, notably regional seas conventions, some of which are promoted by the United Nations Environment Programme (UNEP), and many of which produce regular quality status reports. Regional initiatives are underpinned by national laws and regulations that, despite differing global inequalities, are broadly similar across countries.

Climate change, biodiversity loss and pollution

Climate both influences and is influenced by oceanic conditions, and climate change is regarded as a range of exogenic unmanaged pressures in a marine area. While the causes of climate change emanate outside that area, requiring them to be managed globally, the consequences, such as increased storminess, erratic weather patterns and acidification, are within that area

and so require local management, including adaptation to relative sea-level rise. The recent IPBES thematic assessment report on interlinkages among biodiversity, water, food and health (2024)[13] emphasizes the intertwined nature of biodiversity loss, climate change, public health, food, water and energy, among other things. These influence coastal livelihoods and sustainability prospects.

The IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC, 2019) and the sixth IPCC assessment report[14] show global climate change trends and future projections under different greenhouse gas scenarios (the so-called shared socioeconomic pathways scenarios (see sect. 4, chap. 3; and subsect. 5B)). Global carbon dioxide (CO_2) emissions increased from 30.4 $GtCO_2$ in 2010 to 37.55 $GtCO_2$ in 2023. This has decreased polar and altitudinal ice cover and sea oxygen levels and increased ocean acidification and extreme events such as coral bleaching (see sect. 4, subchap. 5D).

The loss of Arctic sea ice is opening navigation routes and therefore access to previously inaccessible resources, as well as providing increased vectors of non-indigenous species (NIS) (see sect. 4, chap. 6). There will also be increased demand for resources, such as water for agriculture in increasingly arid areas, and the movement of fish stocks polewards. Climate change and its growing marine pressures are increasing human population migrations, not least from arid interior areas to coastal areas, but also from vulnerable coastal areas.

Biodiversity loss both reflects and indicates a decline in ocean health and is therefore a driver for associated changes such as a loss of ecosystem services and the resulting societal goods and benefits (UNEP, 2020). It also weakens ecosystem resistance and resilience to threats, including climate change, pollution, NIS input and overfishing, further accelerating the decline in ocean health (UNEP, 2020).

Contamination and pollution, such as plastic waste, agricultural run-off, sewage and chemicals, are major contributors to the decline in ocean health (UNEP, 2021). Nutrient pollution from agricultural run-off and urban and industrial discharges cause eutrophication, resulting in harmful algal blooms that deplete oxygen in the water, cause fish kills and create abiotic "dead zones" (UNEP, 2016). Plastic pollution creates significant environmental concerns. The ocean water column is a major, transitory sink for microplastics, forming a suspended concentration (Harris and others, 2023). This and the increasingly large major gyres of ocean-floating plastics have led to negotiations on a legally binding treaty to cover the full life cycle of plastics (Maes and others, 2023).

In addition, plastics and harmful chemicals such as heavy metals and pesticides are experiencing bioaccumulation, disrupting reproduction and growth, and entering the food chain to affect larger organisms, including humans (Maes and others, 2020; Elliott and Kennish, 2024). This degrades critical habitats such as coral reefs and mangroves, reducing biodiversity and essential ecosystem services, including coastal protection and carbon storage (Halpern and others, 2008; Harris and others, 2021). Furthermore, increased CO_2 emissions have led to ocean acidification, negatively affecting shell-forming organisms and disrupting marine ecosystems. Pollution thus poses a significant threat to ecosystem health, resistance and resilience, requiring effective pollution management and mitigation.

3. Key region-specific issues or aspects associated with drivers

There are geographical variations in all drivers described in the present chapter, especially between the global North and the global South, but also in terms of economic wealth, population demographics, technological status and susceptibility, such as to climate change and geopolitical instability and the resulting impacts.

Population growth and demographic changes

Fertility rates and therefore population growth in high-income regions, notably the global North, continue to be lower than in middle- and low-income regions, especially in equatorial areas and the global South (Baxter and others, 2017). However, fertility rates coupled with an ageing demographic, even in high-income countries,

[13] See www.ipbes.net/nexus-assessment.
[14] See www.ipcc.ch/assessment-report/ar6.

creates challenges, although population growth in such countries results partly from economic and climate change migrants (legal and illegal entries). There is high population growth in sub-Saharan Africa, Central and Southern Asia and Eastern and South-Eastern Asia. The average in the least developed countries[15] was 2.3% over the period 2015–2020, over twice the rate globally. This influenced the achievement of sustainable development and the conservation of coastal and marine areas, especially in areas vulnerable to climate change, climate variability and sea-level rise (United Nations Department of Economic and Social Affairs (UNDESA), 2019).

Migration to coastal areas (Ekoh and others, 2023) requires increased adaptation of coastal cities to climate change (Wannewitz and others, 2024). Although globally not uniform, the rise in the number of global coastal megacities from 25–33 in 2018 to 44–45 in 2023 puts more populations at risk of flooding, erosion, subsidence and increased storminess and storm surges.

In 2022, the global total fertility rate was 2.3, the same as the global fertility replacement rate for 2010–2015, thus creating a significant milestone at which the global fertility rate equals the global replacement rate.

Economic growth

The global financial crash in 2008 and the COVID-19 pandemic increased economic challenges and the variable abilities of rich and poor countries to withstand such shocks; for example, political instability, the effects of conflicts and/or climate change have adversely affected economic growth. Changes to shipping routes, including the opening up of Arctic routes, and accidents or piracy affect global trade (e.g. diversions from the Suez Canal).

It is notable that, together with increased economic growth globally, coastal and estuarine urbanization and industrialization have increased disproportionally but with international and intranational discrepancies. Rising wealth in some areas and a growing middle class, especially in the global South, have increased tourism and recreation, with greater coastal development and infrastructure. In 2024, global international tourism reached 97% of pre-pandemic levels and had increased in some areas.[16] Similarly, agricultural changes and deforestation produced demographic changes.

Technological advances

Marine technological advances, especially in areas beyond national jurisdiction, expand sustainable inclusive ocean economies and the exploitation of marine resources. This includes increased aquaculture and renewable-energy extraction moving offshore and proposals for deep-sea mineral mining. Effective international governance, such as through the International Seabed Authority (ISA) and the United Nations Convention on the Law of the Sea, is required to enhance national cooperation and address international transboundary issues, especially to obtain societal goods and benefits while at the same time protecting marine ecological structure and functioning. Technology transfer is needed between the most and least developed countries and regions to ensure the sustainable development and exploitation of marine resources. This also includes increased monitoring of activity, environmental pressures and impacts and the conservation of nature protection areas as actual or de facto marine protected areas (MPAs) (see sect. 3).

There have been recent technological developments for controlling the consequences of sea-level rise, with increasing estuarine barriers and hard defences, nature-based solutions, habitat creation and the setback of defences. However, the continued loss of mangroves and other protective vegetation reduces coastal protection from both sea-level rise and increasing storminess and storm surges. Where sea defence costs outweigh the value of the assets being protected, communities are encouraged to move back from the coast; however, a lack of financial capability in less-developed, low-lying areas, such as the Sundarbans in India and Bangladesh, prevents such adjustment.

Technological improvements in fisheries extraction reduce by-catch, and improved aquaculture technologies allow for the movement of mariculture and windfarms offshore. A move from fixed to floating cages and turbines and underwater current turbines enables exploitation of deeper waters, in other words increased marine industrialization. Ocean carbon capture and storage technologies as well as CO_2 removal are being trialled (Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), 2019, 2025), as are hydrogen storage technologies for energy created by renewable sources.

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15 See www.un.org/ohrlls/content/about-us.

16 See www.untourism.int/news/international-tourism-reached-97-of-pre-pandemic-levels-in-the-first-quarter-of-2024.

The offshore oil and gas industry is undergoing a major transformation as fields are exhausted or deemed unnecessary. Injection techniques extract the remaining oil and gas but the major transition is through decommissioning, including decisions on whether to remove, leave or topple the rigs and jackets in place, and to leave or remove pipelines and cables. For example, "rigs to reefs" programmes, with their advantages and disadvantages for local biodiversity, and investment in decommissioning technologies are being considered in oil- and gas-producing areas in the Gulf of Mexico, the North Sea and South-East Asia.

Changing governance structures and geopolitical instability

With neoliberalism on the rise, nationalism and protectionism continue to increase, according to the Democracy Index,[17] with notable politically motivated real or threatened trade tariffs and agreements. The Index fell from 5.55 in 2014 to 5.44 in 2019 and 5.37 in 2020, driven largely by the regional deterioration of conditions in Latin America and sub-Saharan Africa. This is the lowest global score since the first Index in 2006, and has significantly deteriorated, occurring largely, but not solely, as a result of government-imposed restrictions on individual civil liberties worldwide in response to the COVID-19 pandemic.

The fall in the global score in 2020 reflected declines in average regional scores worldwide, especially a large decline in the regions of sub-Sahara, North Africa and the Middle East dominated by "authoritarian regimes", where scores declined by 0.09–0.10 points between 2019 and 2020. Average regional scores have declined during the lifetime of the Democracy Index: in both Western and Eastern Europe by 0.06; in Asia and Australasia, the region that has made the most democratic progress, by 0.05; in Latin America by 0.04 in 2020, marking the fifth consecutive year of regression for the region; and in North America by only 0.01, reflecting a larger decline of 0.04 in the United States of America and an improvement for Canada. There remain large regional differences: countries in Scandinavia, the far north of North America (Canada and the northern United States) and the South-West Pacific had the highest indices, while those in sub-Saharan Africa, the Middle East and parts of Asia had the lowest.

These changes have an impact on the adoption of global, regional and national treaties, agreements and legal instruments, thereby affecting economic growth, technological developments and use, and ocean governance, and hence the use and users of the marine environment.

The Organisation for Economic Co-operation and Development (OECD) Better Life Index (OECD, 2020) reflects societal quality based on 11 topics (housing, income, jobs, community, education, environment, civic engagement, health, life satisfaction, safety and work-life balance) as indicators of the ultimate drivers of basic human needs and improved human health and welfare. Between 2010 and 2020, and following the financial collapse in 2008, overall longevity, income, employment and life satisfaction increased, as there were fewer people in overcrowded households. However, there are large and wider inequalities within and between countries, in resources for future well-being (in economic, natural and social capital) and in health outcomes and the environment. Coastal and marine natural, economic and social risks, especially climate change, biodiversity loss and threats to democratic processes, are threatening future well-being.

Cooperation between regional and international organizations increases the ability to tackle transboundary issues, facilitating coherence and equivalence across jurisdictional boundaries (Elliott and others, 2023).

The governance of marine nature conservation and restoration areas varies regionally and geographically. There are geographical disparities in their adoption despite the increase in nature conservation designations and other areas of designated importance (area-based management tools). These include MPAs and other effective conservation measures and their expansion beyond territorial waters (Amorim and Elliott, 2026) (see sect. 3). In addition, ecologically and biologically significant areas, while not designations in themselves, provide crucial scientific guidance for identifying areas of ecological value and are increasingly used as de facto designated areas for conservation, as in Canada.

Climate change, biodiversity and pollution

Climate change pressures show considerable geographical variability, with many areas warming, and ocean acidification, sea-level rise and biodiversity patterns changing with species migrations, ultimately affecting societies (UNEP, 2024) (see sect. 4, chap. 3; and subsect. 5B,

[17] See www.eiu.com/n/campaigns/democracy-index-2020.

chap. 2). National responses to climate change are shaped by policy priorities, including alignment with international climate agreements such as the Paris Agreement and domestic approaches to energy transition.

Climate change effects vary geographically and create hotspots defined according to their vulnerability and the rate of change of their climatic conditions (Fan and others, 2021). These include marine and coastal areas such as the Arctic, Western Africa, the central eastern coast of South America (Brazil to Uruguay), Antarctica, Indonesia and South-East Asia, the Persian Gulf and the Red Sea, and the eastern China area. These areas appear to be warming more quickly and are exposed to species migrations and other consequences of climate change.

These hotspots have to cope regionally and nationally with the consequences of climate change, whereas the causes have to be addressed globally and with coordinated action, including by China, the United States, India, Europe, the Russian Federation and Brazil, which in 2023 accounted for the majority of greenhouse gas emissions (UNEP, 2024).

Coastal areas, deltas and estuaries are especially vulnerable to increases in marine storminess, storm surges, catchment rainfall changes, marine heatwaves and hurricane frequency. Coupled with stressors from increasing coastal urbanization and industrialization, they cause infrastructure destruction. It is therefore necessary to focus on natural hazards that become risks when they affect human welfare. For example, annual numbers of hurricanes in the North Atlantic Ocean were 2–9 in the 1980s; 3–11 in the 1990s; 3–15 in the 2000s; 2–12 in the 2010s; and 7–13 in 2020–2023.[18]

4. Outlook

Coastal urbanization and industrialization and ocean industrialization, and the economic repercussions thereof, are projected to continue increasing in all geographical areas, thereby providing food, shelter, employment, well-being and enjoyment, inter alia, as well as stressors. Informal settlements will proliferate around many cities in the global South, together with the exposure of low-lying coasts to sea-level rise and climate-compounded risks in the coming decades and centuries (Barbier, 2015). Those activities each have a footprint in terms of the natural system, leading to increasing pressures footprints and even larger effects footprints (Elliott and others, 2020). Activities are accompanied by the increased technological exploitation of ocean resources, including wind and wave energy, biotechnology resources and minerals – the latter necessary for batteries in electric vehicles.

The range of climate change pressures, state changes and impacts on human welfare will continue at the present rate even if greenhouse gas production decreases. Technological advances aimed at increasing adaptation to global warming using methods in, below or above the oceans may progress beyond the development stage (GESAMP, 2019, 2025). Further coastal defences will be required to combat storm surges, flooding and erosion. The effects of climate change will have an impact on the structure and functioning of ecosystems and ultimately the creation and use of societal goods and benefits.

As well as geopolitical instability, national, regional and global demographics will change with economic migration, varying fertility rates and notable ageing populations in the global North and an increasingly youthful population in the global South; these will all have an impact on coastal and marine ecosystems and the extraction of marine resources. Governance changes at the local, national, regional and global levels need to be vertically integrated (from the local to the global level and vice versa) and horizontally integrated across the main sectors of sustainable inclusive ocean economies. Governance instruments require coordination and funding to deliver marine use sustainably and stressors will require monitoring, modelling and management. Many national administrative and statutory bodies will be increasingly responsible for protecting marine areas and species using several nature conservation designations, including in areas beyond national jurisdiction.

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction, which entered into force on 17 January 2026, will play a crucial role in governing areas beyond national jurisdiction. While the Convention primarily upholds the principle of freedom of the high seas, the Agreement is designed to ensure the sustainable use and conservation of marine biodiversity in areas

[18] See https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=northatlantic.

beyond national jurisdiction, through effective implementation of the relevant provisions of the Convention and further international cooperation and coordination. Its implementation, including capacity-building and the transfer of marine technology, and area-based management tools are expected to enhance cooperation among stakeholders, reinforcing collective responsibility in addressing challenges in areas beyond national jurisdiction.

The value of sustainable inclusive ocean economies has been estimated at a minimum of $1.5 trillion per year, which is projected to double by 2030, with total ocean assets (natural capital) estimated at $24 trillion.[19] This will be achieved by means of existing and new technologies, especially as renewable-energy generation replaces fossil fuel extraction, which is facing the economic and environmental challenges of decommissioning. Shipping will be able to exploit new Arctic polar sea routes (specifically the Northern Sea Route and the North-West Passage) due to an increase in ice-free periods; however, this will expose formerly pristine areas to pollution threats and increase NIS spread. Short-sea transport, especially inshore ferry routes, may use alternative fuels, such as energy stored in batteries.

The marine system and its ecosystem structure, function, services, goods and benefits are subject to local, national, regional and global risks and hazards, including shocks. These create, modify and disrupt the drivers, activities and pressures discussed in the present chapter. Most notably, the COVID-19 pandemic had major economic adverse repercussions, although some activities were restricted temporarily, such as fishing, tourism, maritime transport and supply chains, and manufacturing, resulting in decreased contamination and greenhouse gas emissions.[20] However, economies have mostly recovered and in some sectors, such as international travel and tourism, activity is now back to pre-pandemic levels. The short-, medium- and long-term effects of the pandemic on marine ecosystems and the uses and users of the seas have yet to be fully realized.

5. Key remaining knowledge and capacity gaps

The drivers, activities and pressures described in the present chapter interact, and although the single effects are well known conceptually and qualitatively, if not quantitatively, the cumulative synergistic and antagonistic effects are poorly understood (Korpinen and others, 2019). The spatial and temporal quantification of activity, pressures and effects footprints is still lacking but is needed to quantify the overall human footprint on the marine system.

A holistic, integrated assessment, management and governance system is needed for the sustainable use and protection of the marine environment as a socioecological system (Elliott and Kennish, 2024; Borgad and others, 2019; Smith and others, 2025). This ensures that national, regional and global economies are protected and that the well-being of growing populations is assured. Both the ecosystem-based approach, operationalized by ecosystem-based management, and the precautionary approach, are therefore important. These are supported by adopting fit-for-purpose monitoring systems linked to quantitative indicators, which will indicate what type of management is required and also whether management has been effective (Elliott and others, 2025) (see sect. 3). Despite this, ecosystem-based management is only one of several approaches as governance imperatives (Glavovic, 2024).

The prediction of effects relies on detailed field and laboratory science coupled with modelling, including end-to-end models linking natural functioning and socioeconomic outputs. Furthermore, monitoring and management systems should be effective in all regions and areas. This detailed science then needs to inform policy, and vice versa. Transferring marine science and management technologies and approaches across geographic areas, especially from the global North to the global South, will have positive outcomes. In particular, such capacity-building will create sustainably managed global oceans and seas.

Crucial in this wider context is the need to engage with marginalized groups, Indigenous Peoples, gender and other forms of inequity and injustice, as these realities drive unjust and unsustainable development. Overcoming the drivers and root causes of unjust and unsustainable coastal and ocean development is therefore not a technical problem but a socioeconomic and political challenge.

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19 See https://thecommonwealth.org/bluecharter/sustainable-blue-economy.

20 See www.carbonbrief.org/analysis-coronavirus-has-temporarily-reduced-chinas-co2-emissions-by-a-quarter.

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Chapter 2
Scientific understanding

Key points

- The ocean is a single and complex interconnected system, the planet's "life-support system", combining biological, physical and chemical processes while interacting with the atmosphere. It hosts millions of species, many still unknown.
- Managing human impacts on the ocean is essential for preserving life on Earth, including humankind. Despite advancements, significant challenges persist, necessitating ongoing improvements to ensure long-term sustainability.

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1. Introduction

A comprehensive scientific understanding of the ocean and its complex functioning (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), 2020) is essential for assessing human-induced impacts.

Evidence-based science underpins this effort, integrating disciplines, including marine biology, ecology, ethology, physical and biological oceanography, climatology, geology, marine chemistry, genetics, acoustics, economics, sociology, ocean literacy and traditional knowledge.

An integrated multidisciplinary approach addresses societal challenges, improves the understanding of oceanic complexities, identifies knowledge gaps, enhances sustainable uses, preserves spiritual values and ecosystem services and supports Sustainable Development Goal 14. Advances since the publication of the second *World Ocean Assessment* are detailed in each chapter of the third *Assessment*.

Nonetheless, the ocean is increasingly threatened by acidification, warming (see sect. 4, chap. 3), eutrophication (see sect. 4, chap. 3), plastics pollution (see sect. 4, chap. 6), deep-sea mining (see subsect. 5A, chap. 7) and anthropogenic noise (see sect. 4, chap. 6). Persistent organic pollutants (POPs; see sect. 4, chap. 6), heavy metals and radioisotopes (see sect. 4, chap. 6) from human activities, along with overfishing and illegal, unreported and unregulated (IUU) fisheries (see sect. 4, chap. 1; subsect. 5A, subchap. 1A; and subsect. 5B, chap. 5), remain critical issues.

A significant milestone was the adoption in 2023 of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction following two decades of negotiations. This marks significant progress towards better ocean management.

Improving scientific knowledge is essential for enforcing the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction and advancing Sustainable Development Goal 14.

2. Advances in data, theories, technology and models, including enhancing socioeconomic understanding

The symposium organized in 2023[1] by the Division for Ocean Affairs and the Law of the Sea of the Office of Legal Affairs of the United Nations, in collaboration with IOC-UNESCO, and multidimensional indications (Boero and others, 2019a, 2019b; Qiao, 2024; IOC-UNESCO, 2024) provided an opportunity for useful science-policy discussions, supporting enhancements to the Sustainable Development Goals, particularly Goal 14.

Advancements since the second *World Ocean Assessment* include:

- The Intergovernmental Panel on Climate Change (IPCC, 2023) improved data, forecasts and ocean understanding.
- Technological improvements boosted knowledge of ocean health, climate processes and the complex ocean ecosystem, as follows:
  - Combining in situ data with satellite remote-sensing assimilation technology has produced a consistent global meteorological data set since 1958, improving physical oceanography (European Centre for Medium-Range Weather Forecasts (ECMWF), 2024; National Oceanic and Atmospheric Administration (NOAA))[2] (see also subsect. 5A, chap. 6).
  - Drones improve real-time data collection (Fillingham and others, 2023) (see also sect. 4, subchap. 5G; and subsect. 5A, chap. 2, subchap. 3B and chap. 9).
  - Artificial intelligence progressively improves prediction capacity, although integrating partial artificial intelligence models into existing broader numerical models remains challenging

[1] See www.un.org/regularprocess/sites/www.un.org.regularprocess/files/summary_of_discussions_symposium_final_for_circulation.pdf.

[2] See www.star.nesdis.noaa.gov/data/star_docs/meetings/2018JPSSAnnual/Thursday/5_0_Garrett_LunctimeBB_DataFusion_v2.pdf.

(Ebel and others, 2024). Improving data-sharing remains essential.

  - Marine microbiome studies in the most remote areas and assessments of ecosystem health are now possible using new sequencing technologies and environmental DNA (Haddock and Choy, 2024) (see also subsect. 5A, chap. 5).
  - Ocean warming is evident not only at the surface but also at depths below 2,000 m globally (Cheng and others, 2024; Johnson and Purkey, 2024).

- Improved taxonomical, genetic and ecological studies have expanded knowledge of deep-sea biodiversity. Newly identified species include 33 species of cephalopods, 7,252 species of invertebrates and 3,502 species of fishes (see sect. 4, chap. 5 and subchaps. 4B, 4C and 4D).
- Conservation status has improved for, among others:
  - Eastern Atlantic bluefin tuna (International Commission for the Conservation of Atlantic Tuna (ICCAT), 2022)
  - Southern bluefin tuna (Commission for the Conservation of Southern Bluefin Tuna (CCSBT), 2023; International Seafood Sustainability Foundation (ISSF), 2025)
  - Four subpopulations of loggerhead turtles (International Union for the Conservation of Nature (IUCN), 2023)
  - Mediterranean monk seal (Valsecchi, 2024).
- Management tools and initiatives have improved, including advancements in marine spatial planning (see sects. 1 and 3). Efforts to decarbonize shipping (International Maritime Organization (IMO), 2023) and reduce underwater noise and other ecological impacts are advancing (Marine Environment Protection Committee (MEPC), 2023; Shuye and Lidong, 2024).
- Socioeconomic studies have improved for shipping, fisheries, marine aquaculture, oil extraction, coastal activities and deep-sea mining (Benites and others, 2023; de Matos and others, 2023; Bin Hassan and others, 2024).

Policy and international activities include:

- The European Union mission "Restore our Ocean and Waters" (2020) initiated hundreds of new projects, including the European Digital Twin of the Ocean, marking a significant step towards sustainable ocean management (Könnölä and others, 2021). By combining real-time data, artificial intelligence models and simulations, digital twins of the ocean create virtual representations of the ocean that can support better decision-making and ocean governance.
- The United Nations General Assembly (2024) highlighted the importance of well-structured marine geospatial information management infrastructure for sustainable ocean development.[3]

3. Key region-specific changes

Arctic Ocean

The Arctic Council monitors climate change impacts, including sea-level rise, altered density in the northern Atlantic and a slowing Gulf Stream (Piecuch and Beal, 2023). These changes drive species, including pathogens, from the Pacific into the Arctic and the Atlantic. Ice melt has also opened new shipping routes, raising pollution risks, with significant environmental, social and economic implications.

North Atlantic Ocean, Baltic Sea and North Sea

The Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission) (OSPAR Commission, 2023a) updated the status of the North East Atlantic, noting improvements since the publication of the second *World Ocean Assessment*, such as a decrease in concentrations of POPs. However, concerns remain, including ocean acidification, noise pollution and the declining status of marine birds (see sect. 4, subchap. 4G). Climate change is probably the greatest pressure affecting plankton (see sect. 4, subchap. 4A) and endangers coastal and benthic habitats. Protection of the Sargasso Sea[4] is advancing (Mackey, 2021; Roe and others, 2022).

The Baltic Sea assessment (Baltic Marine Environment Protection Commission (HELCOM), 2023) showed that

[3] See www.un.org/Depts/los/doalos_publications/publicationstexts/MarineGeospatialInfoMgmt.pdf.

[4] Mostly promoted by the Sargasso Sea Commission and various non-governmental organizations.

climate change increases risks of biodiversity loss and aggravates the impact of existing pressures.

Mediterranean Sea and Black Sea

The Mediterranean Sea and the Black Sea host rich biodiversity but face growing pressures. Climate change and shipping drive increasing numbers of immigrant species (Galanidi and others, 2023), threatening local biodiversity and complicating management efforts. Studies are now focused on oceanographic changes and their effects on the distribution of fish species (Di Natale, 2024). Ongoing conflicts in the Black Sea hinder assessments.

South Atlantic Ocean and wider Caribbean

Recent studies highlight climate change impacts on the Brazil Current, including altered heat transport, upper ocean salinity shifts, deep ocean freshening and intensification, and the poleward shift of the Brazil Current, which contribute to ecosystem changes (Franco and others, 2020; Chidichimo and others, 2023).

Rising surface temperatures in the Caribbean Sea have increased hurricane frequency and intensity, threatening endangered corals and reefs (Hernández-Delgado and others, 2024) and boosting mass blooms and stranding of pelagic *Sargassum* species (Robledo and others, 2021).

Along the Brazilian continental margin, new seafloor morphologies and habitats have been discovered, including carbonate constructions, siliciclastic drifts and multiple submarine canyon systems (Steinmann and others, 2020; Alves and others, 2023; Jovane and others, 2024; Tagliaro and others, 2024). Challenges persist in controlling invasive species, offshore salmon farming and fisheries for shrimps and squids (Seto and others, 2023; de Carvalho-Souza and others, 2024).

Understanding of the ocean system in the Gulf of Guinea has improved (De Esteban and others, 2023).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

An anticyclonic gyre in the central Indian Ocean induces the downwelling of nutrients, reducing productivity and mesopelagic organisms (Jena and others, 2013; Cherel and others, 2020). The Agulhas Current generates highly productive mesoscale eddies between Madagascar and Africa (Annasawmy and others, 2018; Vianello and others, 2020). The Indonesian Throughflow has been reassessed (Fritz and others, 2023).

International research surveys have improved understanding of pelagic diversity, distribution, migration and trophic and biophysical interactions, as well as the impact of warming temperatures (Ternon and others, 2014; Annasawmy and others, 2020a, 2020b, 2022a, 2022b, 2024a, 2024b, 2025). Indian Ocean warming extends to 750 m in depth, with deep cooling observed in the subtropics (Wenegrat and others, 2022). Plastic pollution remains an important threat (Woodall and others, 2015; Fürychová and others, 2024).

North Pacific Ocean

The North Pacific Marine Science Organization improved model approaches, using multidisciplinary components (Lew and others, 2024). Ecosystem assessment methods (Hunsicker and others, 2022; Kobari and others, 2022) have been reviewed to enhance tools and capacity-building, improving future regional understanding of the ocean. Prediction models for large pelagic species have been included to cover long-term predictions in different environmental scenarios (Muhling and Chen, 2020).

The China Ocean Agenda 21 has incorporated the 2030 Agenda for Sustainable Development in order to promote marine protection. In 2023, the Marine Environmental Protection Law was improved to integrate land-sea management (Information Office of the State Council, 2024).

Tropical (central) Pacific Ocean

This area is a major biodiversity hotspot, but also an area strongly affected by climate change.

Many of the coral reefs in this region, such as in the Cook Islands and the Great Barrier Reef, face repeated bleaching (Henley and others, 2024). The vaquita (*Phocoena sinus*), a critically endangered porpoise, continues to approach extinction in Baja California (Rojas-Bracho and Taylor, 2021; International Whaling Commission (IWC), 2023).

El Niño and La Niña complicate the understanding of climate change, affecting species distribution, especially for tunas. The combined effects have environmental, economic and social impacts. New long-term models (Barrier and others, 2023) aid their management, using updated scientific understanding.

Marine litter and rising sea levels are increasingly threatening islands and communities.

The Association of Southeast Asian Nations (ASEAN, 2025) is developing new initiatives to facilitate the inclusive use, management and conservation of oceanic resources and cooperation in the marine sector.

South Pacific Ocean

Pollution from many sources, climate change and El Niño are worsening marine environments (Atalah and Sanchez-Jerez, 2020). Concerns remain over regional and high-seas fishery management (Food and Agriculture Organization of the United Nations (FAO), 2024) and increasing deep-sea mining (Schofield, 2018). Plastic pollution and its impact on marine life are increasing (Muñoz-Pérez and others, 2023; Savoca and others, 2021). Oceanographic modelling is improving (e.g. www.fishmip.org).

Southern Ocean

This remote region is difficult to study (Antonello, 2018; Howitt, 2024). Understanding is advancing through active and passive ocean observation and modelling (Gray, 2024). Ocean circulation, which is crucial to global processes, and the carbon cycle are driven by complex interactions of ice, sea level and oceanic processes across wide spatial and temporal scales (Bennett and others, 2024; Gray 2024; de Souza and Morrison, 2024). Sea ice is a key component of the ecological web in this region (Swadling and others, 2023) (see sect. 4, subchap. 5K).

4. Outlook for scientific understanding of the ocean

Due to the ocean's size and complexity, understanding of its functions and the human impacts on it, although progressing, remains limited. The discovery of "dark oxygen" in 2024 suggests many more secrets that are currently unknown (Sweetman and others, 2024).

Climate change tipping points, such as phase change in the Labrador Sea, the subpolar gyre and/or the Atlantic Meridional Overturning Circulation, require further study. Understanding of cumulative impacts will benefit from a mainstream approach, for example by adopting a four-dimensional ocean approach (latitude, longitude, depth and time). The complexity of marine biodiversity, including microbial communities, is much broader and more complex than is currently understood.

Autonomous and biomimetic underwater vehicles, autonomous surface vehicles and uncrewed surface vehicles are revolutionizing high-resolution marine data collection. Sailing vessels opportunistically collect marine data and water samples during oceanic races in remote areas.

Advanced modelling and artificial intelligence are enhancing scientific understanding of the ocean. Environmentally driven prediction models for large pelagic fish reveal large-scale oceanic changes (Petrik and others, 2020).

New analytical techniques improve knowledge of the distribution, role and pathological effects of nanoplastics for marine life and humans (Catarino and others, 2022; Zaki and Aris, 2022; Chaoli and others, 2024).

Improved seafloor mapping, a flagship programme of the United Nations Decade of Ocean Science for Sustainable Development (Seabed 2030; see IOC-UNESCO, 2025), advances understanding of benthic and deep environments for management and conservation.

A key emerging challenge is the underwater noise impacts of fixed and floating offshore wind farms on migratory pelagic species (Hendon and others, 2024).

Gradual warming increases risks for Indigenous Peoples and coastal communities (IPCC, 2023). Cross-disciplinary and transdisciplinary studies could improve by being expanded to support informed decisions integrating biological, environmental, social and economic approaches for a sustainable ocean, providing a more holistic approach to Sustainable Development Goal 14.

5. Key remaining knowledge gaps

Despite the ocean's importance, Sustainable Development Goal 14 remains the least funded of all the Goals (Conrad and others, 2022), affecting oceanic research. Key gaps were identified by IOC-UNESCO (2024) and the third *World Ocean Assessment*:

- Seafloor mapping remains limited to 27.3% (Seabed 2030; see IOC-UNESCO, 2025).
- Little of the vulnerability of marine biodiversity, species genetics and microbial communities, particularly

in the deep sea, to climate change and emerging economic activities is understood.

- Understanding of microbial diversity and its role and function in biogeochemical processes is still very limited.
- There are faster climate change impacts on ocean circulation and cumulative effects on the ocean-atmosphere interface and on marine communities and species, including population dynamics.
- Marine and coastal ecosystem-based management can be supported by scaling up collaboration and data collection to address multiple stressors.
- Research output from the global South is often underrepresented, as there is reduced capacity-building relative to the global North.
- Understanding of POPs and emerging unregulated pollutants, along with cumulative health effects on living species, is still limited.
- Understanding of underwater anthropogenic noise impacts on marine species and migrations is very limited.
- Knowledge of chemical and biological processes of polymetallic seafloor deposits is poor.
- Understanding of plastics and nanoplastics dynamics in the ocean and their biological effects is extremely poor.
- Sustainable ocean plans require stronger evidence-based decision-making and national oceanic accounting systems.
- Climate-resilient oceanic economy projects need better conservation and socioeconomic integration for local communities.
- Scaling up climate mitigation, including renewable energy and coastal ecosystem management, is essential.
- Marine carbon dioxide (CO_2) removal feasibility, impacts and policies require urgent study.
- Risk assessment tools for coastal communities and marine industries need development.
- Investment in ocean science and digital representation requires new financial models.
- Greater effort is needed to preserve and catalogue Indigenous, traditional owner and local community knowledge.
- A large but unknown proportion of historical scientific information is not yet available digitally and remains inaccessible to those who need the information.
- Regional fishery management organizations (RFMOs) are working on improving the integration of multidisciplinary ocean management and climate change in their approach through outreach to their contracting parties.

6. Key remaining capacity gaps

Sectoral gender gaps are decreasing, but persist in some areas (see subsect. 5B, chap. 6). Regional capacity gaps remain (Potter and Pearson, 2023). Partnerships and cooperation are transversal tools for improving capacities.

Uniformity in infrastructure distribution needs improvement, including specialized multidisciplinary scientific capacity, remote-sensing tools, modern oceanographic instruments, autonomous vessels, research ships and modern land-based support laboratories. Ocean data would benefit from increased or improved calibration with in situ measurements. Despite advances in modelling and forecasting, capacity gaps between advanced and developing economies remain significant. Artificial intelligence might help.

Gaps in biodiversity knowledge persist due to declining taxonomic expertise (Boero, 2001; Löbl and others, 2023) and the underutilization of international funding (Boero, 2010), limiting marine biodiversity research.

Several capacity gaps in ocean science were identified under the United Nations Decade of Ocean Science for Sustainable Development (Arbic and others, 2024), including: language barriers, underrepresentation of marginalized groups (women, persons with special needs, early-career professionals, Indigenous Peoples, etc.) and limited data accessibility. A more open data-sharing system can reduce capacity gaps. The Decade coordination office for ocean data-sharing is a crucial tool for collaboration and improving access to ocean science data (Decade Coordination Office for Ocean Data Sharing, n.d.).

7. Emerging issues

Recovery of existing scientific knowledge

Scientific and cultural ocean knowledge, gathered over centuries, is scattered across thousands of documents around the world, which are often unavailable digitally. This knowledge is crucial for understanding marine environment evolution and the historic exploitation of ocean resources (Niner and others, 2024), but is often not available digitally. While some organizations, such as Google, the Digitisation Centre of Western Australia and the Digital Public Library of America, are making efforts to recover and publish such information, ensuring its accessibility (Kaspar and others, 2015; Di Natale, 2022), there is still a large amount of information that is not accessible. Although limited to information from the most recent decade, improving the ocean literacy programme under the United Nations Decade of Ocean Science for Sustainable Development will also assist with this process.

Indigenous Peoples and local coastal community knowledge

Coastal, island and Indigenous Peoples communities hold ancient cultural knowledge about the ocean, including on marine species, seasonality and natural phenomena (Vierros and others, 2020; Pardie and Campion, 2022; Strand and others, 2022) (see sect. 5, particularly subsect. 5A, chap. 7, and subsect. 5B, chaps. 2 and 8). Traditional boat-building techniques and marine gear design are derived from the ancient experiences of global coastal communities. This precious knowledge is at risk of disappearing if not urgently recovered for future generations and for current management (Kaiser and others, 2019). Ethno-anthropologists are essential in this effort. Preserving this knowledge not only safeguards history but also supports future marine research, providing essential baselines for long-term environmental assessments and policy development.

A new paradigm: ocean rights

The principles of ocean rights were presented to the General Assembly in 2023 after extensive international discussions. A legal paradigm shift is needed to ensure the adoption of the Universal Declaration of Ocean Rights by 2030,[5] safeguarding the planet's "life-support system". While not formally endorsed, this innovative approach will provide a comprehensive legal framework for United Nations bodies and stakeholders, aligned with existing universal declarations (Bennett and others, 2024).



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[5] See www.earthlawcenter.org/ocean-rights and www.theoceanrace.com/en/ocean-rights.

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Chapter 3
Trends in the physical and chemical state of the ocean

Key points

- Tracking changes in the physical and chemical properties of ocean regions is critical to understanding the future of the planet, with significant geopolitical and socioeconomic consequences.
- These changes are under way, and nations will need to plan to adapt to them strategically to minimize damage to ecosystems and communities that rely upon them.
- Since the publication of the second *World Ocean Assessment* (see chap. 5 thereof), trends continue to reflect accelerated warming and sea level rise in the global ocean, as well as prominent regional increases in surface salinity, particularly in the mid-Atlantic and southern Atlantic, and decreases in annual global sea ice coverage.
- These changes are affecting global water circulation and air-sea-ice interaction processes while also leading to changes in nutrient distribution, species shifts (see sect. 4, chap. 4) and accelerating ocean hazards (see subsect. 5B, chap. 4). There will be significant changes to coastal ocean dynamics associated with sea level rise, warming and shifts in circulation, leading to significant impacts on regional communities over the next few decades. One of the most impactful changes anticipated is the frequent occurrence of an ice-free Arctic Ocean in September by the middle of the twenty-first century.

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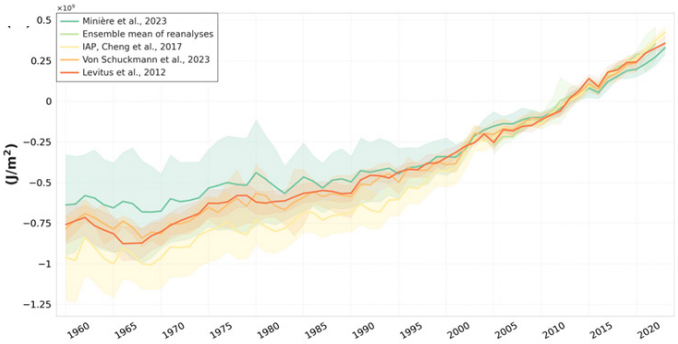
1. Physical trends

Ocean temperature (including ocean heat content)

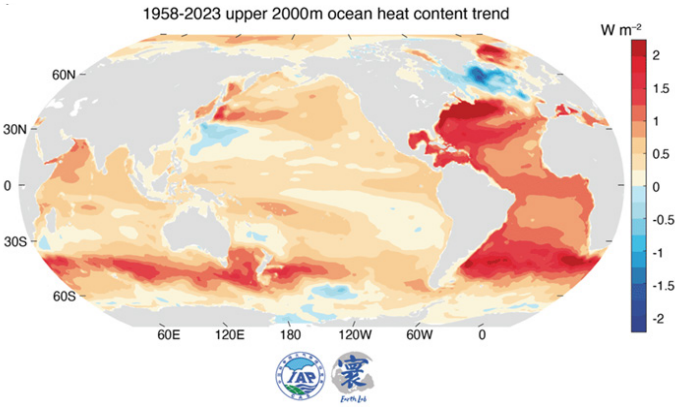
The great capacity of the ocean to capture and store heat moderates the temperature of the planet. Over 90% of the heat absorbed by the Earth since 1955 has been accumulated in the oceans. Figure I (a) illustrates the heat increase in the upper 2,000 m of the ocean since 1955 and shows a continuous rise that peaks in 2023 (von Schuckmann and others, 2024). Some 16% of this increase occurred between 2018 and 2023 even though those years represent only 7% of the time period. This heat energy accounts for 30% to 50% of sea-level rise in the ocean through thermal expansion. In addition, warming contributes to changes in the migration of oceanic species, damage to coral reef systems and the accelerated melting of ice sheets (see sect. 4, subchap. 5K; and subsect. 5B, chap. 4). While the Pacific Ocean holds the largest heat reservoir due to its vast size, the greatest warming has been observed in most of the Atlantic Ocean and in the parts of the Southern Ocean adjacent to the Indian and western Pacific Oceans (see figure I (b)), with notable cooling regions observed in the North Atlantic (~50–70°N) and in the North-West and South-West Pacific (Cheng and others, 2022; von Schuckmann and others, 2024). The ocean surface is where the most important heat exchange between the ocean and the atmosphere occurs. Shifts in sea surface temperature translate to important differences in water evaporation rates, atmospheric heating and cooling, marine heatwaves and the thawing of sea ice, in addition to broader impacts on continental climate, as discussed in the second *World Ocean Assessment*.

Figure I

(a) Global mean ocean heat content (0–2,000 m)



(b) Regional trends of ocean heat content (0–2,000 m)



Source: von Schuckmann and others, 2024.

Note: (a) Global mean ocean heat content (60°S–60°N) integrated from the surface down to a depth of 2,000 m based on different products. Shaded areas indicate the uncertainty of each method. The trend is estimated using a locally weighted scatterplot smoothing approach and amounts to 0.58 ± 0.13 W m^{-2} over the period 1960–2023 and 1.05 ± 0.17 W m^{-2} over the period 2005–2023. (b) Regional trend in the period 1958–2023 for ocean heat content in the upper 2,000 m, in W m^{-2}.

Ocean salinity

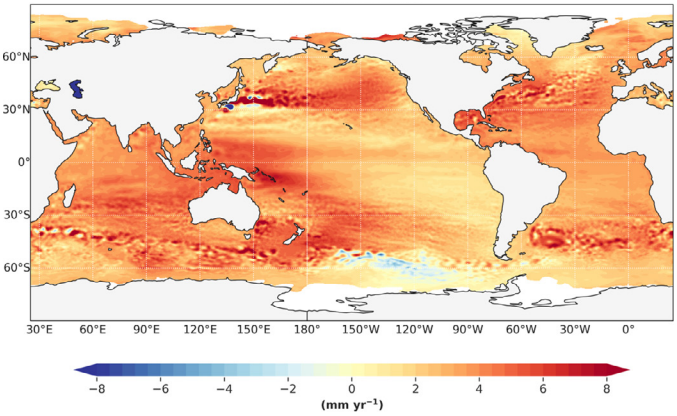
The warming climate is causing an intensification of the global water cycle due to increased rates of ocean evaporation. The impacts on ocean salinity vary based on whether a region will experience greater net evaporation (raising salinity) or greater net precipitation (reducing salinity). The long-term trends indicate that there has been relative freshening or salinity decreases over the entire Pacific, North Atlantic and Southern Oceans, but salinity increases in the mid-Atlantic, southern Atlantic and Indian Oceans (Cheng and others, 2020). These trends are expected to continue throughout the century, likely spanning the 0–1,000 m layer, with a further increase in salinity by 4% to 8% in a world warmed by +2°C (expected in 2046).

Sea level

Sea-level rise is driven mainly by the combination of thermal expansion and extended ice sheet melting. In some coastal zones, additional changes in storm surges and waves and local tectonic or isostatic processes may contribute to absolute sea-level changes of up to a few millimetres per year. Locally, storm surges and waves may account for up to 10% of the sea-level rise (Jevrejeva and others, 2023). The simultaneous occurrence of storm surge and spring tides, resulting in storm tides, adds a significant threat to coastal communities (Moftakhari and others, 2024). Rates of global mean sea-level rise show an increasing tendency, from 1.3 to 1.9 mm per

year during the period 1901–2015 to 2.1 mm per year for the first 10 years of the altimetry era (1993–2002) and 4.3 mm per year for the past 10 years (2013–2023), with faster rates in the Indian Ocean and in some regions of the Pacific and Atlantic Oceans (see figure II). Rates are projected to reach between 5.2 mm per year (lowest carbon dioxide (CO_2) scenario) and 12.1 mm per year (highest CO_2 scenario) during the period 2080–2100 (Fox-Kemper and others, 2021). Sea-level rise is not projected to be uniform up to 2100, as tropical areas seem more likely to undergo the largest changes. Extreme sea-level scenarios under storm conditions (as a combination of sea surface height associated with storm surges, waves, high tides and a low-probability sea-level rise scenario) may reach 4.2 m by 2100, compared with 2.6 m in the period 1980–2014 (Jevrejeva and others, 2023). Overall, a significant proportion of the world's coasts will be inundated by 2100, although inundation will not be uniform, as countries with flat coasts will be more threatened (Vernimmen and Hooijer, 2023). Further sea-level rise concerns are addressed in United Nations technical reports (United Nations Framework Convention on Climate Change (UNFCCC), 2024).

Figure II
Regional sea-level trends, January 1993 to June 2023



Source: Adapted from von Schuckmann and others, 2024.

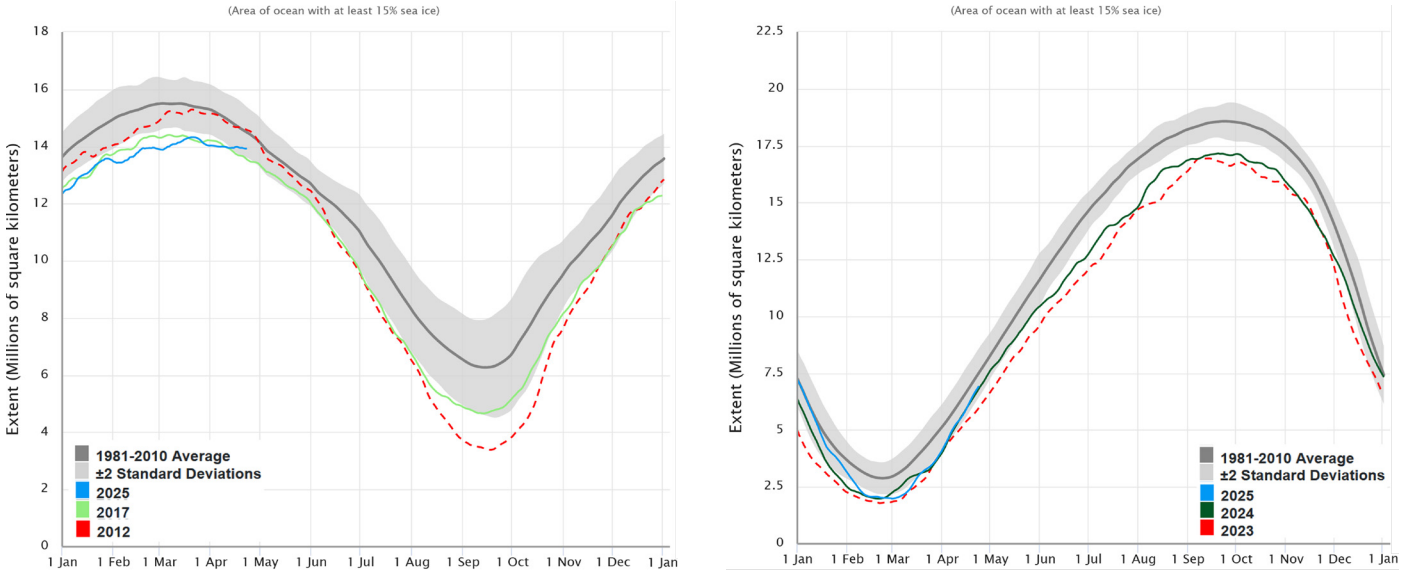
Sea ice

The well-documented decrease in Arctic sea-ice extent (more precisely, in Arctic Ocean and other northern hemisphere areas with seasonal ice cover) continues (Meier and others, 2023; Stroeve and others, 2025), and in the period 2021–2025 seasonal sea ice extent remained close to the lowest in the satellite record for the period from 1979 to the present. The area of multi-year ice (>4 years old), as well as the age, thickness and volume of sea ice, have remained consistently low since the 2010s and close to minimum values for the period of observations from 1979 to 2025, with the marginal ice zone moving further north in the summer (Thoman and others, 2023), although significant regional and seasonal positive variations do occur. On 22 March 2025, Arctic winter ice reached a minimum extent of 14.33 million km^2, below the prior low of 14.41 million km^2 in 2017 (see figure III). In the most recent climate predictions based on the Climate Model Intercomparison Project 6, the earliest ice-free[1] conditions could occur in the 2030s under all emission trajectories and are likely to occur by 2050 (Jahn and others, 2024). Consistently ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by the middle of the twenty-first century (2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice-free.

In contrast to Arctic sea ice, the extent of sea ice in the Southern Ocean has only very recently (since 2021) shown a significant decrease, with the record minimum summer and winter sea ice observed in February and September 2023 (Purich and Doddridge, 2023). Southern Ocean declines in sea ice are most pronounced in regions south and west of the Antarctic Peninsula. The impacts of such decreases are widespread, including changes in dense shelf water and associated Antarctic Bottom Water formation, and increased heating of surface waters with subsequent changes in stratification and mixing dynamics. On 1 March 2025, Antarctic Sea ice reached its minimum extent of 1.98 million km^2, tying for the second lowest extent with 2022–2024 in the 47-year satellite record (see figure III).

[1] The use of the term "ice-free" in the present chapter should not be confused with the navigational term "ice-free" used by relevant United Nations bodies such as the World Meteorological Organization (WMO) or the International Maritime Organization (IMO). Since icebergs will continue to be present within the domains of the Arctic and Southern Oceans, the navigational term "ice-free" is not applicable here.

Figure III
Arctic and Antarctic sea-ice average and extreme extents



Source: https://earth.gsfc.nasa.gov/cryo/data/current-state-sea-ice-cover.

Note: The red dashed lines indicate the current record minimum extents for the summer (Arctic, 2012) and for the summer and winter (Antarctic, 2023), and the grey line and zones in the time series indicate the average for 1981–2010, with a standard deviation range of +/-2.[2]

Global ocean circulation patterns at all scales, including vertical and horizontal patterns such as stratification, and boundary currents

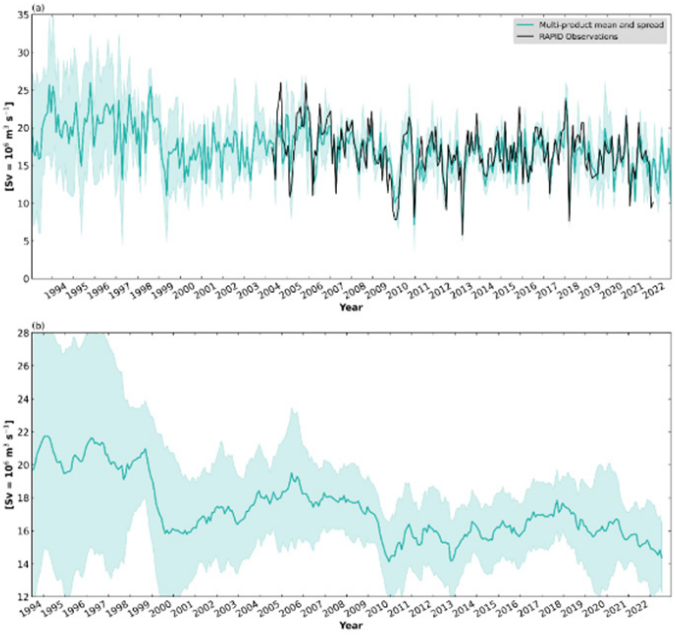
The potential decline of the Atlantic Meridional Overturning Circulation is a major concern related to ongoing changes in global circulation patterns. Previous results from Climate Model Intercomparison Project 5 had predicted the slowdown of the Atlantic Meridional Overturning Circulation, and some models predicted an abrupt collapse during the twenty-first century. However, weakening during the twenty-first century (see figure IV) has a medium to low confidence level and none of the models in Climate Model Intercomparison Project 6 predict the collapse of the Atlantic Meridional Overturning Circulation during the present century. A weakening of northward heat transport would result in a decrease in sea surface temperature and surface atmospheric temperature in the North Atlantic subpolar gyre, ultimately reducing the delivery of heat to northern Europe. Swingedouw and others (2021) estimated that the probability of this cooling was 45.5% in Climate Model Intercomparison Project 5, but had decreased to 36.4% in Climate Model Intercomparison Project 6. On the other hand, Caesar and others (2018, 2021) found that the Atlantic Meridional Overturning Circulation was weakening and could reach a tipping point and abrupt collapse during the mid-twenty-first century (van Westen and others, 2024). This would result in significant climate shifts in the northern hemisphere, particularly in Europe, followed by significant shifts globally due to the redistribution of ocean heat energy. Changes in the Atlantic Meridional Overturning Circulation remain a research priority.

These changes in heat and freshwater transport in the North Atlantic are likely related to changes in the South Atlantic and Indian Oceans. According to the Intergovernmental Panel on Climate Change (IPCC) (2019), the Agulhas leakage, an inflow of anomalously warm and saline water from the Indian Ocean into the South Atlantic, has intensified since the 1960s, contributing to the warming of the upper 300 m in the South Atlantic. The Agulhas leakage is likely to continue to increase during the twenty-first century contributing to the slowdown of the Atlantic Meridional Overturning Circulation (Loveday and others, 2015). This intensification of the Agulhas and Benguela currents would be produced by an intensification of westerlies in the southern hemisphere and the southward displacement of the southern currents. This result should, however, be further analysed carefully in

[2] See https://nsidc.org/sea-ice-today.

the future. Majumder and Schmid (2018) used temperature and salinity profiles from Argo profilers and sea surface height data to calculate the transport associated with the Agulhas Current and found no significant changes since 1993.

Figure IV
Temporal evolution of Atlantic Meridional Overturning Circulation strength at 26.5°N



Source: Adapted from von Schuckmann and others, 2024.

Note: Temporal evolution of the Atlantic Meridional Overturning Circulation strength at 26.5°N obtained by integrating meridional transport at 26.5°N across the Atlantic basin (zonally) and then cumulatively integrating over depth. The green line and shading (twice the standard deviation) are based on modelled products. The black line shows the observational record from the RAPID array (Moat and others, 2025). Panel A shows monthly mean values, and panel B shows inter-annual variations by applying a 12-month running mean.

Against a backdrop of ocean warming, freshening changes to Arctic Ocean oceanography induced by declining sea ice are certain, as reviewed by Timmermans and Marshall (2020). Decreased summer sea ice is resulting in reduced reflection of solar radiation back into space (reduced albedo) and an associated increase in surface ocean mixed-layer temperatures at a rate of about 0.5°C per decade. Additional trends in increased heat advecting from the Pacific Ocean have triggered increased sea ice decline in the Chukchi Sea at the fastest rate of sea ice decline of the entire Arctic Ocean. The Atlantification of the Arctic Ocean, resulting from increased Atlantic water layer heat fluxes into the Eurasian basin, is resulting in reduced sea ice and changes in stratification (Polyakov and others, 2023, 2025). The total freshwater content of the Arctic Ocean continues to increase, especially in the Beaufort gyre region (increase of liquid freshwater content from 2003 to 2018 by 40% relative to the climatology of the 1970s) as a result of persistent anticyclonic atmospheric wind forcing, sea ice melt, a wind-forced redirection of the Mackenzie River discharge and a contribution of low-salinity waters of Pacific Ocean origin through the Bering Strait (Proshutinsky and others, 2019). In the Arctic shelf seas, there has been a decrease in freshwater content, combined with deeper mixed layers as winds drive surface freshwater offshore.

In general, there has been a freshening and warming of the Southern Ocean and associated increased stratification of the uppermost 200 m since the 1970s. This potentially restricts the vertical exchange of heat, salt, nutrients and gases between surface, intermediate and deep waters (Carter, Bostock-Lyman and Bowen, 2022). The freshening of Antarctic shelf waters in Southern Ocean surface waters has led to a freshening and contraction of Antarctic Bottom Water formed in the Weddell Sea, Cape Darnley, the Adélie coast and the Ross Sea. This trend is certain to have profound implications in slowing down deep ocean ventilation and global overturning circulation (Gunn and others, 2023; Lee and others, 2023; Li and others, 2023) and in turn on marine productivity, with a consequent impact on fisheries. The societal implications of these changing resources are profound (Huntington and others, 2022; Stroeve and others, 2025).

2. Chemical trends[3]

Ocean acidification

About 20% to 30% of the CO_2 released by human activity into the atmosphere has been absorbed by the ocean, leading to an increase in the average surface ocean acidity of 0.1 pH units since pre-industrial levels. The transport of CO_2 to the deeper ocean via currents and mixing has meant that ocean acidification now surpasses a depth of 2,000 m in the North Atlantic and Southern Oceans (IPCC, 2022). International initiatives such

3 Trends in contaminants are described in sect. 4, chap. 6.

as the Global Ocean Acidification Observing Network are reporting large spatial and temporal variability in carbonate chemistry in the coastal zones as consequences of biological activity, water mixing and run-off from land. There is a large body of evidence reporting the negative impact of ocean acidification on marine species, ecosystems and their associated services (see sect. 4, chaps. 4 and 5). Species adaptation to changes in carbonate chemistry has been utilized as one of the representative stressors studied to understand species and ecosystem sensitivity (Vargas and others, 2022) in future marine conditions (Widdicombe and others, 2022).

Changes in carbon

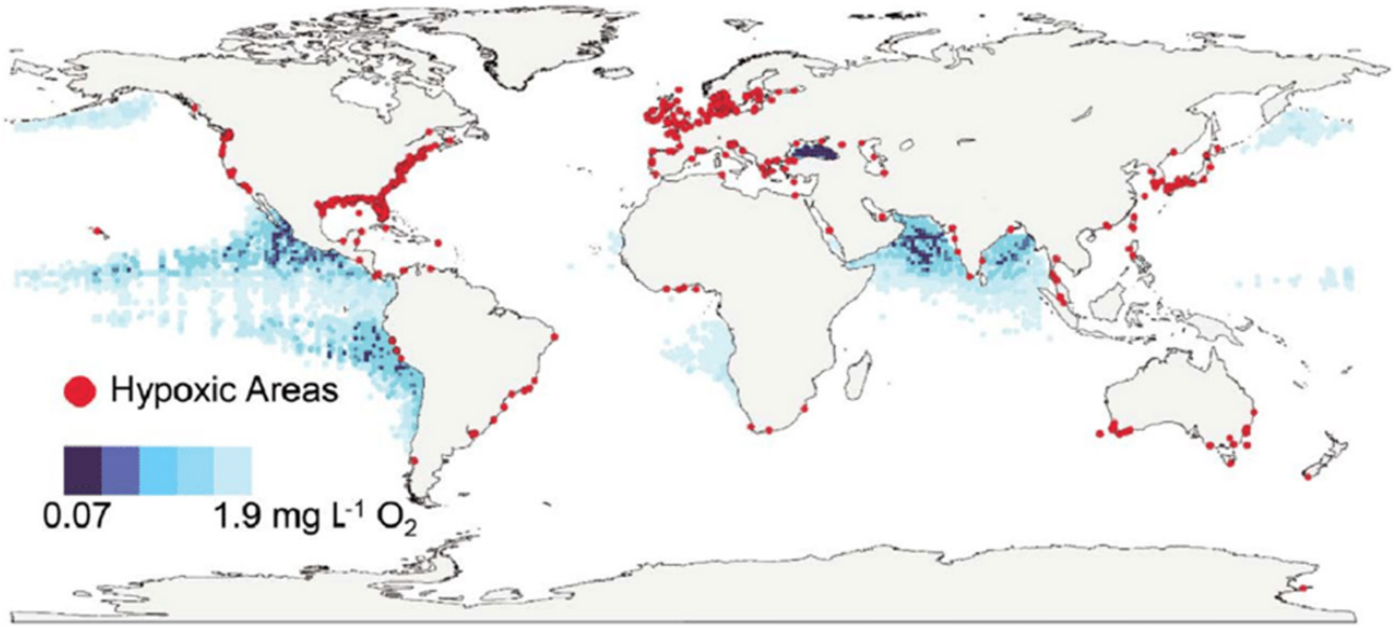
The ocean is the second-largest carbon reservoir on Earth at 37,300 GtC (10^{15}gC) and holds over 60 times the carbon of the atmosphere (DeVries, 2022). Ocean CO_2 uptake rates have tripled over the past 60 years to 2.7 ± 0.3 PgC per year (over the period 1990–2019) and are expected to continue increasing by 0.4 ± 0.1 PgC per decade (Gruber and others, 2023). These values are affected spatially and inter-annually by shifts in weather and climate. It is expected that eventually the average net warming of surface waters will reduce ocean uptake rates due to the reduction in CO_2 solubility at higher temperatures.

Total alkalinity is a measurement of the buffering capacity of the ocean or its ability to counter changes in pH and is dominated by inorganic carbon (i.e. bicarbonate and carbonate). Total alkalinity in subtropical regions has increased due to changes in the global water cycle (increased evaporation) and is expected to continue to do so. The northern hemisphere has more spatial variability in total alkalinity and salinity than the Southern Ocean due to fewer changes in salinity and the contribution of upwelling of total alkalinity-enriched waters (Fine and others, 2017).

Dissolved oxygen

The trend of global deoxygenation in the oceans continues and is driven by a combination of lower oxygen solubility associated with increasing water temperatures, intensified stratification (particularly in the open ocean) and higher nutrient additions to primarily coastal areas that drive bacterial activity and oxygen consumption. Figure V shows the areas with increasing oxygen minimum zones (blue) and coastal areas that are experiencing primarily anthropogenically driven hypoxia (red). It should be noted that over the past 50 years the hypoxic zone area has increased by 4.5 million km^2 and the world's oceans continue to lose roughly 1 GtO_2 per year (Keeling and Garcia, 2002), decreasing by more than 2% (4.8 ± 2.1 petamoles) since 1960 (Schmidtko and others, 2017).

Figure V
Ocean minimum zones (blue) and areas with coastal hypoxia (red) in the world's ocean



Source: GO2NE, 2018. Adapted from Isensee and others (2015) and Breitburg and others (2018), including oxygen effects from Keeling and Garcia (2002), Diaz and Rosenberg (2008) and Carstensen and others (2014).

Nutrients

Nitrogen

Since 2018, changes in the climate have significantly altered oceanic nitrogen dynamics, affecting phytoplankton productivity, carbon sequestration and greenhouse gas emissions (see sect. 4, subchaps. 4A and 5N). Although ocean warming, changes in stratification and acidification are major influences on the ocean's nitrogen cycle, ocean deoxygenation is expected to have one of the largest impacts on microorganisms involved in nitrogen transformation pathways (Hutchins and Capone, 2022). Adaptable anammox bacteria in oxygen-deficient zones (Zhao and others, 2024) reflect diverse responses, and increased nitrogen fixation rates linked to higher diazotroph richness underscore the role of biodiversity (Shao and others, 2023). Comparing recent studies with historical data such as the World Ocean Atlas II reveals differing trends across regions, emphasizing the need for ongoing monitoring to capture dynamic regional responses to climate change (Pitcher and others, 2021), such as in the Southern Ocean, where regional variability in nitrogen dynamics and phytoplankton responses reflect localized impacts (Boyd and others, 2024). Understanding these complexities is crucial for predicting climate feedback and guiding effective mitigation strategies.

Phosphorus

Since 2018, studies have highlighted shifting oceanic phosphorus availability and cycling driven by climate change. Changes in ocean temperature, stratification and circulation affect phosphorus availability and cycling (Gerace and others, 2025). Further studies have demonstrated the significant role that phosphorus plays in nitrogen fixation by important groups of phytoplankton, with implications for marine productivity and ecosystems (Moisander and others, 2022; Boyd and others, 2024). These recent studies highlight deviations in contemporary phosphorus trends from historical baselines, emphasizing the need for updated monitoring to accurately predict future biogeochemical cycles.

Silica

Rising ocean acidification lowers the dissolution rate of biogenic silica and therefore increases the burial rate in sediments (Taucher and others, 2022). This is expected to favour diatoms that require silicic acid to grow and account for nearly 40% of marine primary productivity in the short term. Over the long term (150 years), the increased burial of silica will lead to silica limitation, which may have a negative impact on diatom productivity and shift the primary production assemblages in the global surface ocean waters. The areas most affected are expected to be those undergoing the fastest rates of acidification, particularly coastal zones where burial rates are greatest.

3. Gaps

There remain important uncertainties in mechanistic understanding of how ocean circulation will respond to warming and changes in freshwater inputs, especially at regional scales. The ocean is an important distributor of heat on the planet and any changes in circulation patterns alter how heat will be distributed. In addition to heat, circulation patterns determine where and when nutrients will be depleted and replenished, which is translated to regional ecosystem dynamics, regional fisheries and regional economies. To improve the ability to predict future conditions and plan for and achieve some degree of resilience in response to the changes, it is necessary to invest in observations (including long-term time series) and models in key regions and help communities to prepare and adapt infrastructure planning. These include the areas known to be changing most rapidly, such as the Arctic Ocean and the Southern Ocean. It is also necessary to identify ecosystem thresholds where key species are most at risk, in order to avoid fisheries collapse. These efforts are critical to inform communities and help to guide adaptive management.

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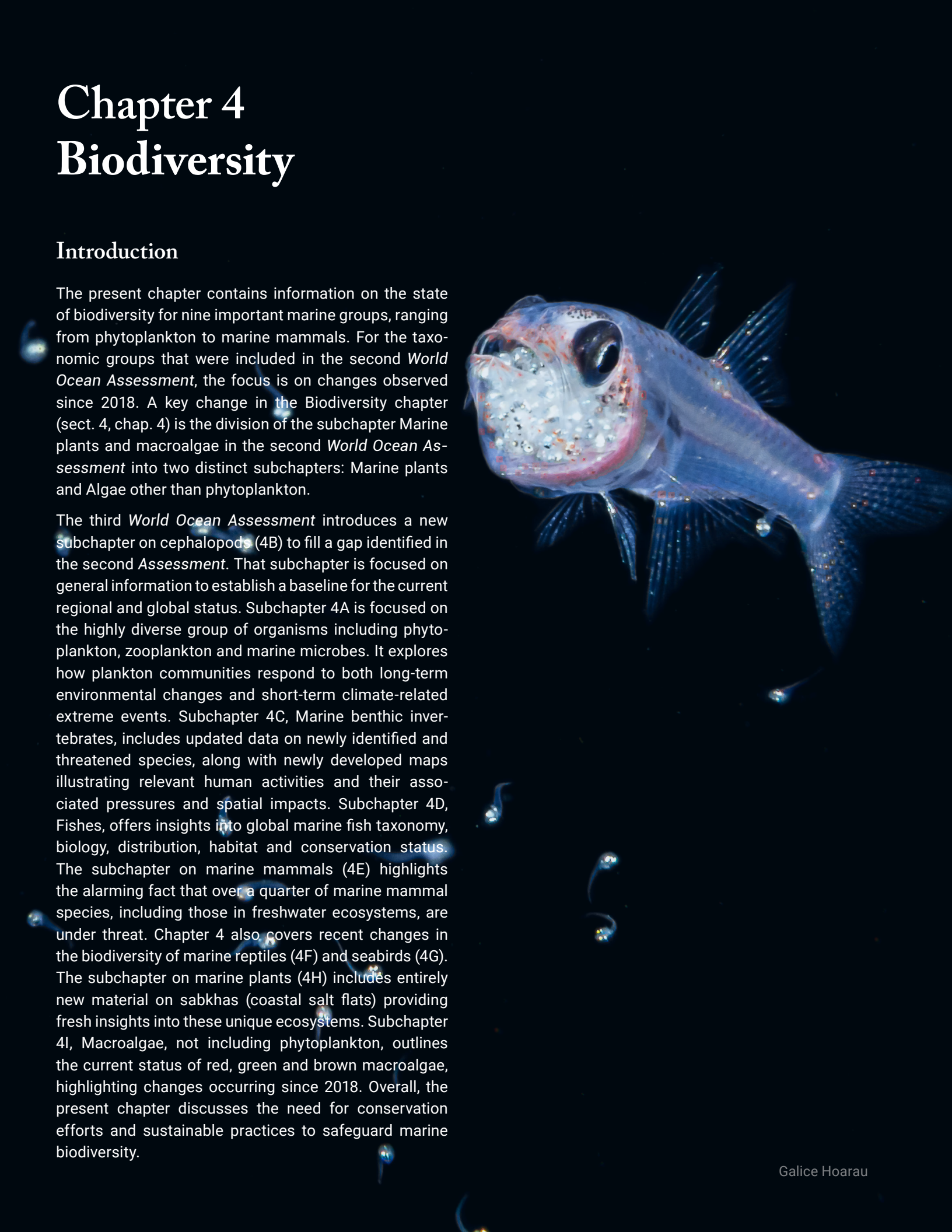
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Chapter 4
Biodiversity

Introduction

The present chapter contains information on the state of biodiversity for nine important marine groups, ranging from phytoplankton to marine mammals. For the taxonomic groups that were included in the second *World Ocean Assessment*, the focus is on changes observed since 2018. A key change in the Biodiversity chapter (sect. 4, chap. 4) is the division of the subchapter Marine plants and macroalgae in the second *World Ocean Assessment* into two distinct subchapters: Marine plants and Algae other than phytoplankton.

The third *World Ocean Assessment* introduces a new subchapter on cephalopods (4B) to fill a gap identified in the second *Assessment*. That subchapter is focused on general information to establish a baseline for the current regional and global status. Subchapter 4A is focused on the highly diverse group of organisms including phytoplankton, zooplankton and marine microbes. It explores how plankton communities respond to both long-term environmental changes and short-term climate-related extreme events. Subchapter 4C, Marine benthic invertebrates, includes updated data on newly identified and threatened species, along with newly developed maps illustrating relevant human activities and their associated pressures and spatial impacts. Subchapter 4D, Fishes, offers insights into global marine fish taxonomy, biology, distribution, habitat and conservation status. The subchapter on marine mammals (4E) highlights the alarming fact that over a quarter of marine mammal species, including those in freshwater ecosystems, are under threat. Chapter 4 also covers recent changes in the biodiversity of marine reptiles (4F) and seabirds (4G). The subchapter on marine plants (4H) includes entirely new material on sabkhas (coastal salt flats) providing fresh insights into these unique ecosystems. Subchapter 4I, Macroalgae, not including phytoplankton, outlines the current status of red, green and brown macroalgae, highlighting changes occurring since 2018. Overall, the present chapter discusses the need for conservation efforts and sustainable practices to safeguard marine biodiversity.



Galice Hoarau

Subchapter 4A
Plankton

Key points

- Plankton are overwhelmingly the biomass-dominant organisms in the open oceans; thus, their activity sets the rates of biogeochemical cycles and propagates to higher trophic levels.
- With short generation times, large population sizes and high diversity, plankton are responsive to changing ocean conditions. However, this responsiveness presents challenges when it comes to capturing changes at the appropriate spatial and temporal scales.
- As addressed in the second *World Ocean Assessment*, it is predicted that the productivity, composition and distribution of plankton will be altered due to global change-driven alterations in temperature, nutrient fluxes and ocean acidification, among other factors (see sect. 3). However, in the absence of observable ecosystem tipping points, the period 2018–2023 largely continued previously observed trends. We identify gaps in data on plankton responses to long-term environmental change, as there is little long-term data aside from that on phytoplankton and zooplankton that can be used to establish trends. However, we identify stronger support for event-driven compositional and functional shifts in response to, inter alia, storms, fires and marine heatwaves.
- Current global observing networks and models still under-sample plankton or treat them as a "black box", failing to capture their dynamics in the pelagic oceans and particularly in dynamic coastal ecosystems (see subsect. 5A, chap. 9).

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1. Introduction

Marine plankton comprise the majority of biomass in the open oceans and drive key biogeochemical cycles and support higher trophic levels by providing essential resources such as food and oxygen. Marine plankton (here excluding larvae of larger organisms) encompass a diversity of forms and functions, including viruses; bacterioplankton; archaea; phototrophic, heterotrophic and mixotrophic microeukaryotes; and zooplankton. Prior World Ocean Assessments and the scientific literature have contained predictions on plankton responses to long-term global change, including temperature-driven poleward shifts and changes in community composition; decreasing phytoplankton cell size due to stratification; reduced transfer of carbon and energy to metazoan food webs and to the deep ocean; reductions in primary production at mid-latitudes and increases at the poles; loss of calcifying taxa due to ocean acidification; shifts towards carnivorous and gelatinous filter-feeding zooplankton; and high temperatures potentially driving localized extinctions or evolution in the tropics (Bopp and others, 2013; Beaugrand and others, 2019; second *World Ocean Assessment*; Heneghan and others, 2023; Knecht and others, 2023).

Many of these predictions and models, which generally concern roughly the next 100 years, have been focused on primary producers, which tend to have more clearly defined thermal niches and nutrient requirements compared with other plankton groups (Bopp and others, 2013). Particularly neglected are predictions for heterotrophic eukaryotes (e.g. fungi, labyrinthulomycetes) (Jones and others, 2022), which are generally not measured in time series or molecular surveys. In addition to data gaps and biased methods (e.g. exclusion of fragile rhizarians in net samples (Soviadan and others, 2024) or exclusion of specific taxa by molecular techniques), it can be difficult to determine whether shifts in plankton composition are driven directly by global change or indirectly through interactions with other trophic levels. For example, as phytoplankton serve as the base of the marine food web, alterations in their composition and physiology propagate to bacteria and zooplankton consumers (Hunt and Ward, 2015). While there is growing confidence in measurements of environmental change and models of plankton responses (Beaugrand and others, 2019), we lack unambiguous, empirical evidence that long-term climate pressures are reshaping plankton communities. Shifts in plankton abundance and community composition are assumed to be driven primarily by temperature, followed by nutrients and salinity (Frémont and others, 2022). However, many environmental parameters co-vary, and the same characteristics that make plankton good sentinels or bioindicators for ecosystem change, such as short generation times and responsiveness to environmental conditions, make it difficult to identify the proximal drivers of community and biomass changes. Further complicating identification of long-term trends, plankton are also shaped by mesoscale physical and temporal forces, including seasonal changes, large-scale multi-year oscillations (e.g. El Niño/Southern Oscillation (ENSO)), stochasticity and drift (Vellend, 2010).

2. Environmental change since the second *World Ocean Assessment*

Given the vast diversity in plankton phylogeny, trophic levels, form and function, a comprehensive review of the predicted impacts of global change on marine plankton is beyond the scope of the present *World Ocean Assessment* update, which covers the period 2018–2023. Instead, we focus on the evidence of observed responses to: (a) sustained changes in the environment (e.g. ocean warming) as assessed by time series and (b) shorter-term climate-related extreme events (e.g. storms, fires). Research has highlighted not only long-term trends, but also the importance of extreme events, including floods, storms and heatwaves, which may themselves be driven by global change or may add to underlying climate trends (e.g. a marine heatwave occurring alongside long-term warming).

3. Long-term trends

Measuring changes in plankton requires long-term time series to separate annual and inter-annual variability from global change-driven trends. Environmental observations, experiments and models are largely focused

on phytoplankton due to their relatively simple nutrient requirements, the abundant long-term data on them and the ease of measurement. However, even trends in phytoplankton are somewhat mixed within general shifts towards smaller phytoplankton, including cyanobacteria (see table 1). Globally, phytoplankton blooms have increased in area by 13.2% and in frequency by 59% between 2003 and 2020, although with regional differences and compositional changes (Dai and others, 2023). Moreover, despite predicted decreases in tropical ocean primary production, the Hawaii Ocean Time-series shows increasing primary production, driven mainly by higher concentrations of cyanobacteria and picoeukaryotes (Kwon and others, 2022). Similarly, long-term trends in zooplankton reveal mixed responses: in some regions biomass has decreased, while in others there have been increases in biomass and shifts in community composition (Pitois and Fox, 2006; Couret and others, 2023; Fernandez de Puelles and others, 2023).

While it is generally assumed that temperature drives most changes in plankton (Richardson, 2008), other environmental factors play a role in plankton dynamics. For example, a strengthening of the East Australian Current tropicalized temperate cyanobacteria and heterotrophic bacteria and altered phytoplankton community composition (Ajani and others, 2016; Messer and others, 2020). Nutrients represent another key anthropogenic influence on plankton. Harmful algal blooms have increased in geographic range and frequency in coastal areas since the 1980s in response to increased riverine nutrient inputs (Glibert, 2020). Similarly, zooplankton community changes have been attributed to the combined increases in temperature and nutrients (Holland and others, 2023; Marques and others, 2024) or gradients in salinity and oxygen (Peña and others, 2019a). However, we did not find reports of long-term trends for eukaryotic heterotrophs, as they are not measured in many time series (Xie and others, 2021). To add a further complication, viral abundances are rarely measured and are linked to their hosts, rendering it difficult to differentiate global change's direct impacts on viruses from shifts in host communities.

Table

Predicted impacts of global change and extreme events on plankton

	Long-term global change		Heatwaves		Fires		Storms	
	Abundance	Community	Abundance	Community	Abundance	Community	Abundance	Community
Large zooplankton	Mixed	Shifts in composition	Decreasing	Favouring smaller species	Neutral/ minor impact	Minor shifts	Decreasing	Favouring tolerant species
Small zooplankton	Mixed	Shifts in composition	Increasing	Smaller species dominance	Minor increase	Minor shifts	Mixed	Shifts in composition
Eukaryotic phytoplankton	Decreasing	Favouring smaller species	Mixed	Favouring smaller species	Increase	–	Potential increases	–
Harmful algal blooms	Mixed	Mixed	Increasing	–	–	–	Mixed	–
Cyanobacteria	Increasing	Shifts in composition	Increasing	Shifts in ecotypes	–	–	–	Shifts in composition
Eukaryotic heterotrophs	–	Shifts in composition	–	–	–	–	–	–
Bacterio-plankton	Increasing	Shifts in composition	–	Shifts in composition	–	Shifts to tolerant groups	Potential increases	Minor changes

Source: Prepared by the writing team.

Note: A dash indicates inconclusive or non-existent data.

4. Short-term events

The present part of the subchapter contains an examination of a number of short-term extreme events which are themselves the products of global change (table 1). Marine heatwaves, which are persistent anomalously warm ocean temperatures, highlight the thermal sensitivity of plankton communities. However, observed changes in phytoplankton communities during heatwaves, such as a shift towards smaller phytoplankton (Peña and others, 2019b; Brown and others, 2024) or a shift away from frustule-forming diatoms due to low silicate (Arteaga and Rousseaux, 2023), may reflect co-varying environmental changes, including warming and reduced nutrient inputs through stratification. Zooplankton communities may also transition towards smaller, thermally tolerant species, which can reduce grazing pressure on phytoplankton as well as total zooplankton biomass (Huỳnh and others, 2024). With respect to bacterioplankton, heatwaves have shifted the microbiome towards more thermally tolerant taxa and favour rare taxa (Brown and others, 2024.) Moreover, in one system studied, heatwave-induced bacterial community composition changes did not recover once temperatures returned to seasonal averages (Larkin and others, 2020).

Wildfires. Although they are terrestrial in origin, fires can release growth-limiting resources (e.g. nitrogen, iron) through both wind- and water-based dispersal that fuel phytoplankton blooms (Ardyna and others, 2022). While less is known about heterotrophs' responses to wildfires, wildfires can increase marine organic matter (Coward and others, 2022), which could stimulate heterotrophic growth and the remineralization of carbon dioxide.

Storms. Similarly, strong storms (e.g. tropical cyclones), can be multifaceted disturbances that alter a number of environmental factors, making it difficult to identify the proximal drivers of shifts in plankton. Somewhat surprisingly, such storms do not necessarily fuel dramatic or long-term changes in bacterioplanktons, despite altered environmental factors, but appear to transiently drive shifts in the relative abundance of existing taxa and increase photosynthetic biomass, potentially favouring eukaryotic algae over cyanobacteria (Ares and others, 2020; Gronniger and others, 2022; Johnson and others, 2025). Similarly, zooplankton are often resistant to tropical cyclone impacts, except when higher primary production fuels a zooplankton bloom (Topor and others, 2022). Although little is known about eukaryotic heterotrophs, salinity changes and terrestrial or phytoplankton detritus in coastal waters can cause transient blooms of specific microeukaryotes (Duan and others, 2018; Xie and others, 2021).

Other events. While we have focused on a number of discrete events as described above, additional factors, such as ocean oscillations, deoxygenation, nutrient influxes and changes in terrestrial influences (e.g. salinity and terrestrial organic matter) may also influence plankton dynamics. For example, harmful algal blooms resulting in fish kills have been linked to drought conditions influenced by the Southern Annular Mode (Mardones and others, 2021). Ocean deoxygenation (e.g. increases in oxygen minimum zones) are predicted to affect organisms, especially those sensitive to low oxygen levels, but without discernible effect on heterotrophic eukaryotes (Herrera and others, 2019; Li and others, 2024). Due to the severe under-sampling of coastal oceans and the lack of baseline data needed to identify anomalies from a high-variability baseline, it is likely that a number of critical events and responses among plankton are unknown.

5. Region-specific changes

A full review of changes observed in plankton communities at the regional scale is beyond the scope of the present subchapter due to the high diversity of plankton organisms and to the paucity of long-term monitoring programmes. Ratnarajah and others (2023) have recently reviewed long-term zooplankton monitoring programmes, which shows earlier phenology and poleward range expansion of some groups in the North Atlantic and North Pacific Oceans. In the Southern Ocean, Antarctic krill (*Euphausia superba*) and salps showed poleward shifts. However, the seasonality of the pteropod *Limacina helicina* and the distribution of copepod species remained resilient to warming patterns and did not show apparent changes. The absence of patterns observed in other areas can be partially explained by the limited number of long-term monitoring programmes in areas beyond North America and western Europe and particularly in the global South. However, the overall absence of more examples of seasonal or geographical shifts in distribution across all regions can also be related to reduced accessibility

to data from long-term plankton time series (see figure 3 in Ratnarajah and others, 2023). Although there have been significant improvements in automated or semi-automated analyses of plankton, research is hampered by the lack of experts in morphological and molecular identification of a diverse and complex group of organisms.

Other apparent patterns of change have been observed in other taxonomic groups at the regional scale since the second *World Ocean Assessment* (2018–2023) that show the complexity of plankton dynamics and the difficulties of observing conspicuous long-term trends at the global scale.

Arctic Ocean

The most dramatic changes in the Arctic Ocean have been driven by warming and reduced sea ice cover (Ardyna and Arrigo, 2020; see also sect. 4, chap. 3). Increased open water has led to a 30% increase in net primary production, accompanied by the loss of sea ice-associated plankton (Hop and others, 2020; Ardyna and others, 2022). Furthermore, global change is increasing the "Atlantification" of the Arctic Ocean; for example, *Emiliania huxleyi*, a calcifying coccolithophore, has expanded its range polewards (Oziel and others, 2020), among others. These changes in Arctic phytoplankton communities and sea ice affect zooplankton phenology, production and community composition (Wang and others, 2015); however, less is known about other plankton, such as ciliates (Wang and others, 2023)

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

In the Baltic Sea, phytoplankton blooms have occurred one to two weeks earlier over the past two decades, which is associated with increased sunshine and a decrease in strong wind conditions. Higher temperatures are linked with earlier and decreasing diatom blooms and a higher proportion of dinoflagellates (Hjerne and others, 2019). In the Black Sea, shifts in the composition of the dominant species have been observed together with an increase in the proportion of dinoflagellates, particularly in the fall (Stelmakh and others, 2023). In the Mediterranean Sea, the concentration of diatoms is decreasing and the concentration of cyanobacteria is increasing, and the whole Mediterranean Sea is shifting to an eastern Mediterranean state (Hourany and others, 2021).

Pacific Ocean

The warm anomaly in the Gulf of Alaska in 2014 reduced silica supply and led to a switch in community composition from diatoms to dinoflagellates, resulting in an increase in surface ocean chlorophyll during the summer and fall. A more dramatic change was observed in the equatorial Pacific, where the extreme warm conditions of the 2016 El Niño resulted in a major decline of about 40% in surface chlorophyll, which was associated with a near-total collapse in diatoms (Arteaga and Rousseaux, 2023). The 2023 El Niño may have provoked similar dramatic effects, although its consequences for plankton have yet to be documented.

Southern Ocean

This region has experienced greater warming than other regions, resulting in declines in sea ice and nutrient influxes that have led to phytoplankton blooms (Ferreira and others, 2024). However, despite warming, mesozooplankton communities in the South Atlantic and West Antarctic Peninsula did not significantly change, suggesting possible thermal resilience (Tarling and others, 2018). This region is also subject to the influence of short-term events; for instance, a marine heatwave in the western Antarctic Peninsula showed a 60% decrease in microbial community biomass and a shift from a cryptophyceae-dominated community towards nanoflagellates and heterotrophic plankton (Latorre and others, 2023). In addition, the 2019/2020 Australian wildfires were linked to months-long phytoplankton blooms in the Southern Ocean, potentially due to fertilization of iron-limited waters (Tang and others, 2021).

6. Key remaining knowledge and capacity gaps

We advocate for long-term time series to both capture long-term trends and situate extreme events in context, in order to clarify whether these events result in statistically discernible impacts on plankton and persistent altered plankton states. However, we make the case that specific groups (notably, heterotrophic bacteria and eukaryotes) and regions (e.g. the global South and depths below the photic zone) are underrepresented relative to their biogeochemical importance. We also lack long-term data (and event-driven sampling) on bacterioplankton and heterotrophic eukaryotes. Considering these groups' critical functions in decomposing

organic matter and secondary production, global change and extreme events can significantly affect marine biogeochemical cycles. However, we should not discount the fact that non-determinative factors (e.g. drift) shape plankton communities; therefore, care should be taken when interpreting long-term trends as being driven by global change or when predicting the reproducibility of short-term disturbance responses. To understand the dynamics of plankton in the context of climate variability and extreme events, long-term high-resolution plankton observatories are needed, ideally across taxonomic groups, so that transmission of impacts can be tracked across food webs (Hunt and Ward, 2015). Therefore, we advocate for sustained and even expanded support for plankton observatories in the face of a changing climate.

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Subchapter 4B
Cephalopods

Key points

- As of 2024, there are 861 extant species of cephalopods on the planet.
- Most data regarding cephalopod populations and abundance come from fisheries.
- Squids represent most cephalopod landings.
- The region with the highest species richness is the South Pacific Ocean, with 27% of extant cephalopod species.

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1. Introduction

The present subchapter is an update to "Status of pelagic invertebrates: cephalopods", an addendum to volume 1 of the second *World Ocean Assessment*. As a result, we concentrate on the variations in knowledge about cephalopods, as well as their estimated abundance, distribution and functional role in the period 2018 to 2024, which straddle the period between the publication of the second and third World Ocean Assessments. However, additional information is included here because the addendum was brief and somewhat idiosyncratic.

Cephalopods are generally free-swimming holopelagic or demersal marine invertebrates with complex nervous systems and behaviour. They range in size from small (total length <1 cm) to huge (>14.5 m) and in distribution and abundance from solitary individuals to very large schools. Most have short lives and fast growth, and species are found from the intertidal zones (and estuaries in exceptional cases) to the hadal depths, including the water column and benthic environments. In addition to being the targets of fisheries, some species can be important predators and prey within ecosystems. Some are model organisms for biomedical and behavioural research.

Other chapters within this assessment and that are relevant to cephalopods include those on fishing, pollution, climate change, marine mammals and other large predators (e.g. tunas and billfishes), and prey (e.g. plankton and marine benthic invertebrates), as well as chapters on the various marine ecosystems in which cephalopods live. For example, the importance of food web connections was highlighted recently in a publication (Pérez-Puig and others, 2024) showing that sperm whales abandoned a traditional hunting area in the Gulf of California, probably because of the reduced abundance of Humboldt squid there.

2. Environmental change since the second *World Ocean Assessment*

Despite a lack of data on most cephalopod species, it is considered that multiple human activities threaten their populations, including overharvesting through both legal and illegal, unreported and unregulated (IUU) fishing, either as targets or as by-catch, and physical disturbance of habitat (Barrett and others, 2022). Climatic and environmental shifts also affect habitats, including spawning grounds, and cause direct physiological effects, for example, on *Sepia officinalis* (Rosa and others 2013) and *Octopus rubescens* (Onthank and others, 2020). Notably, even when not catching cephalopods, trawl and dredge fisheries can destroy the eggs of bottom spawners, including myopsids, sepiids and most octopods (Food and Agriculture Organization of the United Nations (FAO), 2008).

Changes in overall status

Table 1 summarizes current knowledge of cephalopod diversity on the basis of the World Register of Marine Species (WoRMS, 2024). A total of 861 species are currently recognized, categorized across nine orders in two subclasses. Of these, 33 (3.8%) were described in the period between 2017 and 2024 (averaging >4 n. spp., or about 0.5% of the total, per year) (see table 1).

As of October 2024, the International Union for Conservation of Nature (IUCN) (IUCN, 2024) Red List of Threatened Species assessed 754 cephalopod species, and the cephalopod listing numbers are essentially unchanged from the second *World Ocean Assessment*. The five cirrate octopod species noted previously as "critically endangered", "endangered" or "vulnerable" are threatened as by-catch in deep bottom-trawl fisheries. One cuttlefish (*Ascarosepion apama*), one octopod (*Octopus kaharoa*) and one nautilid (*Nautilus belauensis*) are now "near threatened". In total, 324 species are of "least concern", but most species (422) are "data deficient". The latter includes some commercial species, probably due to inadequacies in data collection (Keller and others, 2015). Because cephalopods exhibit different life histories (Ibáñez and others 2021) and the life cycle of most species is unknown, their distribution, diversity patterns and abundance are uncertain.

At the sixteenth meeting of the Conference of Parties to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the family Nautilidae was listed in appendix II of the Convention. The primary problem facing nautilids is overfishing. No other cephalopods have been included yet in Convention listings.

Table 1
Cephalopod diversity as at 14 October 2024

	Family	Genus	Total species	New species described since 2017
Class Cephalopoda	47	182	861	33
Subclass Nautiloidea	1	2	7	3
Order Nautilida	1	2	7	3
Subclass Coleoidea	46	180	754	30
Superorder Decapodiformes	30	119	444	15
Order Bathyteuthida	2	2	9	3
Order Idiosepida	1	3	8	1
Order Myopsida	2	11	39	0
Order Oegopsida	21	65	177	1
Order Sepiida[a]	3	37	210	10
Order Spirulida	1	1	1	0
Superorder Octopodiformes	16	61	312	15
Order Vampyromorpha[b]	1	1	2	1
Order Octopoda	15	60	310	14

Sources: MolluscaBase (available at www.molluscabase.org on 2026-01-08. doi:10.14284/448); and WoRMS (available at www.marinespecies.org at VLIZ. Accessed 2026-01-08. doi:10.14284/170).

[a] Includes sepiolids and their relatives, considered by many cephalopod systematists/taxonomists to comprise a separate order.
[b] Includes a second species of *Vampyroteuthis*, a taxonomy which has not yet been accepted as valid by many cephalopod systematists/taxonomists.

Most information about cephalopod populations and their abundance comes from fisheries, either through fishery-related surveys (for which quantitative data are more rigorous) or, more commonly, landings (see figure I.A). Cephalopod landings are strongly dominated by the oegopsid squid family Ommastrephidae (figure I.B; Arkhipkin and others, 2015). However, landing data for cephalopods in general frequently combine various species into one common name (see Arkhipkin and others, 2015; Sauer and others, 2021). Confident determination of diversity patterns and the causes of their changes (e.g. for poleward shifts in distribution, as in *Dosidicus gigas*, see Ramos and others, 2017) requires large-scale comparability of abundance data rather than data on presence or absence or on fisheries landings, the latter being the current state of knowledge about most species. Accordingly, assessing populations for conservation or fisheries management proves challenging without precise data collection. For many species, efforts to plan for stock sustainability are further complicated by the absence of joint management plans for transboundary populations, a gap that may have hindered progress towards the achievement of target 14.4 of the Sustainable Development Goals, originally set for 2020. Moreover, the global patterns of species richness in coastal cephalopods are now known from the few independent ecological studies that have targeted cephalopods (see Rosa and others, 2019). The most diverse region is the South Pacific Ocean, with 207 species (table 2).

Table 2
Coastal cephalopod species richness, by region

Region	Species richness
Arctic Ocean	10
North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea	55
South Atlantic Ocean and wider Caribbean	81
Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf	84
North Pacific Ocean	125
South Pacific Ocean	207
Southern Ocean	15

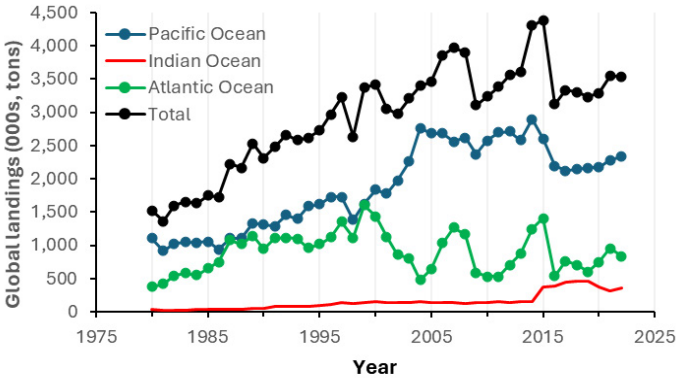
Source: Prepared by the writing team.

Decapod crustaceans and cephalopods are the first invertebrates for which ethical treatment in handling and experimentation is being addressed (Fiorito and others,

2015). They have had protection in regard to research for ethical reasons in Canada and Australia and broader protection in the European Union (pursuant to Directive 2010/63/EU) since 2013 (Fiorito and others, 2015) and the United Kingdom of Great Britain and Northern Ireland since 2022. Protection for research in the United States of America, specifically the banning of octopod farming, is being considered by the National Institutes of Health under its Institutional Animal Care and Use Committee mandate and has been implemented in two states in the United States. Few cephalopods are protected in the wild, but in the United States, the Washington Department of Fish and Wildlife has designated eight dive sites in the Seattle region as Octopus Protection Areas.

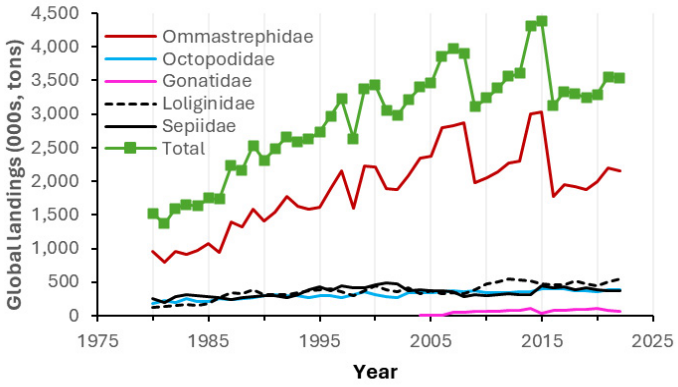
Issues have been raised concerning the field of cephalopod aquaculture. Difficulties concerning artificial cephalopod diets, the potential for environmental pollution and public concern regarding the crowding of solitary octopods, fuelled by popular media, provide arguments against octopus farming (Jacquet and others, 2024; Mather, 2022). However, cephalopod aquaculture is still experimental globally, which presents the perfect opportunity to establish rigorous ethical standards for the practice, both for commercial and restorative purposes (Gleadall and others, 2025).

Figure I.A
Landing totals globally and within major ocean basins



Source: FAO.

Figure I.B
Most heavily fished families, totals



Source: FAO.

3. Region-specific changes

Arctic Ocean

Recent studies of the Arctic (Golikov and others, 2013), compared with earlier work by the Soviet Union, have shown distinct shifts in cephalopod distributions that are consistent with the concept of the "Atlantification" of the Arctic, which refers to climatic changes leading to boreal cephalopods spreading into the polar basin by means of its main connection with the North Atlantic. *Teuthowenia megalops* and *Todaropsis eblanae* have been found in the Arctic for the first time, 1,000 to 2,500 km from their historical ranges. These shifts are also related to the fluctuation of *Todarodes* populations in the main part of their North Atlantic range. Meanwhile, the Arctic species *Gonatus fabricii* has expanded its range to areas where warming is particularly noticeable. This may affect species interactions in vulnerable Arctic ecosystems. This pattern of shifting distributions of Arctic and North Atlantic cephalopods in response to climate change has continued and been further demonstrated with additional long-term data analysed by Golikov and others (2024).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Cephalopod landings are largely composed of octopods and cuttlefishes (Pierce and others, 2010), and come mainly from bottom-trawl fisheries and traditional small-scale fisheries, either targeted or as by-catch, particularly in the Mediterranean Sea and along the Iberian Peninsula (Sauer and others, 2021). Management of cephalopod stocks in European waters remains limited. Each country implements precautionary measures concerning the number of fishing traps and region-specific closed seasons in small-scale fisheries targeting *Octopus vulgaris*. Total cephalopod landings from the North-East Atlantic

have been relatively stable since 1992, but those of cuttlefishes showed high abundance in 2004 and declined in the following years (International Council for the Exploration of the Sea, Working Group on Cephalopod Fisheries and Life History (ICES-WGCEPH), 2023).

The abundance of *Octopus vulgaris* in north-west Africa, particularly off the coast of Morocco, has declined due to fisheries pressure and environmental impacts (FAO, 2020). A catch of 89,000 tons was reported for this region in 2019, accounting for 32% of total demersal catches (FAO, 2020). Octopus holds substantial economic value, particularly in Mauritania, where it is the top fishery resource by value, which underscores the dependence of local economies on this species. The rising global demand for octopus has caused the number of exporting countries to increase, and Japan, Spain and Italy are the primary importers of octopus from north-west Africa (Sauer and others, 2021). In Morocco, *O. vulgaris* is harvested by three main types of fishing fleets: industrial freezer trawlers, artisanal wooden boats employing pots and hand jigs, and coastal ice trawlers utilizing various trawl types. While Morocco has implemented management and conservation measures – such as catch limitations, individual quotas, zoning and restrictions on immature subadult captures – these efforts must contend with the cumulative effects of overfishing and environmental changes driven by climate factors. Therefore, while current regulations are aimed at promoting sustainable fisheries, ongoing monitoring and adaptive management strategies are essential for mitigating the above-mentioned risks.

Regarding taxonomic aspects, with the recent resurrection of *Ommastrephes caroli* (Fernández-Álvarez and others, 2020), new studies have been conducted concerning their biology (see Agus and others, 2021; Petrić and others, 2024). This knowledge provides essential information on the species and can be incorporated into future macroevolutionary studies of cephalopods.

South Atlantic Ocean and wider Caribbean

This region hosts 81 coastal cephalopod species (Rosa and others, 2019). Avendaño and others (2020) debunked the presence of *O. vulgaris* on the western coast and confirmed the distribution of *Octopus americanus* instead. Similarly, the squid species *Ommastrephes cylindraceus* was resurrected by Fernández-Álvarez and others (2020), which will contribute to better delimiting its specific distribution range and concomitantly highlight the relevant implications for conservation and resource management. Another taxon with fishery management implications is *Thysanoteuthis rhombus,* previously considered to be the single species of the family Thysanoteuthidae, which has a global distribution range in tropical and subtropical waters that is now restricted to the North and South Atlantic Ocean and the Mediterranean Sea (Deville and others, 2024).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Fisheries for cephalopods are expanding around the western Indian Ocean (figure I.A), particularly for octopods. Management measures in some countries have increased annual landings. Fluctuations in catch may be an indication of climate-change impacts, natural inter- or intra-annual variability, changes in abundance of stocks or changes in availability due to other environmental drivers or ecosystem shifts.

The Indian Ocean sea regions, including the Arabian Sea, the Bay of Bengal and the southern Indian Ocean, provide a rich and diverse habitat for cephalopods (Aravindakshan and Sakthivel, 1973; Sajikumar and others, 2020). A total of 20 species of commercially important cephalopods have been identified from the Indian coast, which includes eight species of squids (orders Myopsida and Oegopsida), six species of cuttlefishes (order Sepiida) and six species of octopus (order Octopoda) (Mohamed and Venkatesan, 2017). The dominant species occurring in commercial catches are *Uroteuthis (Photololigo) duvaucelii*, *Acanthosepion pharaonis*, *Acanthosepion aculeata* and *Amphioctopus neglectus* (Mohamed and Venkatesan, 2017), with an annual landing of 212,517 tons (Fishery Resources Assessment, Economics and Extension Division, Central Marine Fisheries Research Institute (FRAEED, CMFRI), 2024).

Cephalopod conservation measures in the mechanized fisheries sector are mainly related to fisheries regulations. The Central Marine Fisheries Research Institute of the Indian Council of Agricultural Research has recommended minimum legal size and corresponding body weight for *Uroteuthis duvaucelii* (dorsal mantle length = 80 mm and 25 g body weight), *Acanthosepion pharaonis* (dorsal mantle length = 115 mm and 150 g body weight) and *A. neglectus* (dorsal mantle length = 45 mm and 15 g body weight) (Mohamed and others, 2014) that are legislated and enforced in Kerala, Karnataka and Maharashtra along the south-west coast of India. Cephalopods are targeted mainly by trawlers. The closure of fisheries to all mechanized fishing vessels is applied for 61 days, from 1 June to 31 July, on the west coast (Arabian Sea) and

from 15 April to 14 June on the east coast (Bay of Bengal) as a means of reducing fishing effort and to aid the conservation of fishery resources, including cephalopods.

The Ommastrephidae squid *Sthenoteuthis oualaniensis* occurs in the oceanic waters of all Indian Ocean regions, with high biomass observed in the Arabian Sea (Mohamed and others, 2018). The neon flying squid, *Ommastrephes cylindraceus*, has been studied in the southern Indian Ocean (40°11 S to 47°30 S) (Fernández-Álvarez and others, 2020). The diamondback squid, *Thysanoteuthis rhombus*, is also distributed along the seas around India except the southern Indian Ocean (Sajikumar and others, 2020; Deville and others, 2024). Other non-commercial oceanic squids from the region, such as *Bathyteuthis bacidifera*, *Histioteuthis miranda*, *Abralia andamanica* and *Nototodarus hawaiiensis*, have been studied (Sajikumar and others, 2017, 2018, 2022 and 2023).

North Pacific Ocean

The squid species *Todarodes pacificus* is among the most abundant cephalopod species in the North-West Pacific Ocean. In recent years, the stock size of *T. pacificus* in the North-West Pacific Ocean and its marginal seas has declined, and catches by Japan and the Republic of Korea have declined sharply since 2016 (Okamoto and others, 2023). The stock size of *T. pacificus* is projected to increase due to climate change (Ji and others, 2020). However, despite the rapid rise in water temperatures in the North-West Pacific in recent years, squid stocks have declined. In a marginal sea in the North-West Pacific Ocean, which is one of the main distribution areas, IUU fishing has complicated accurate catch determinations since the 2000s (Park and others, 2020). Determining whether the recent drop in stocks of *T. pacificus* is attributed to fisheries impact or shifts in oceanographic conditions is challenging.

Regarding octopods, in the North-East Pacific Ocean, the species richness of coastal benthic octopuses is higher in the warm temperate region (around 12 species, mainly of *Octopus* and *Paroctopus*) compared with the cold temperate region (around seven species) (González-Gómez and others, 2024).

South Pacific Ocean

All nautilus (*Nautilus* and *Allonautilus*) species inhabit fore-reef slopes across the South Pacific and Indo-Pacific regions to depths of 800 m. Decades of unregulated fishing supporting a worldwide nautilus shell trade (De Angelis, 2012) led to fishery decline (Dunstan and others, 2010) and significantly lower population abundances (Barord and others, 2014). Although the inclusion of nautiluses in appendix II of CITES effectively reduced international trade in them, it is not clear how this regulation will improve the localized management of ongoing fisheries. While population decline and potential local extinction (Barord and others, 2022) are most closely tied to fishing, little information is available on how larger anthropogenic factors may impact nautiluses and their habitat.

Southern Ocean

The Southern Ocean exhibits high levels of cephalopod endemism (Rosa and others, 2019; Cherel, 2020). Fifty-two cephalopod species are recognized for the Southern Ocean, 15 of which are coastal species (Xavier and others, 2018; Rosa and others, 2019). Of the squid species, 21 are endemic (Cherel, 2020).

4. Key remaining knowledge and capacity gaps

Little is known about the life history/life cycle, abundance and ecology of most species, other than those fished commercially or used for biomedical research. This problem is even worse for species in deep-sea and polar regions. Future development of deep-sea mining raises many questions, currently unanswerable, about the impacts of these operations at the individual, population and species levels. However, sustainable measurements are being planned for this economic activity (see subsect. 5A, chap. 7).

Comprehensive genetic studies of most species are needed to identify sub-species and genetically distinct population structures and connectivity, both for proper management of exploited species and for a better understanding of cephalopod roles in their ecosystems, as well as resilience from potential anthropogenic impacts.

Human impacts on cephalopod populations, such as contaminant loads or the effects of harvesting prey or predators, are poorly understood and may counteract

projected increases in cephalopod abundances (Doubleday and others, 2016). The global proliferation proposed by Doubleday and others is based on just a few species. Recent changes in climatic and oceanographic conditions and their likely effects on cephalopod populations (e.g. the effects of increasing acidification on statolith malformation, cuttlebone growth and nautilus shell growth, or of shifts in depth and geographic latitudinal distribution towards warming waters) may also affect future increases. As with many fields of marine science, discipline-specific capacity (e.g. taxonomic and fisheries management capacity) and research tools vary regionally. Regional differences in understanding cephalopods mirror more significant issues, such as the impacts of climate change. Deliberate educational programmes can alleviate such problems.

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Subchapter 4C
Marine benthic invertebrates

Key points

- Seafloor hotspots and 7,252 new benthic invertebrates have been described since the publication of the second *World Ocean Assessment*, and there has been a fivefold increase in critically endangered species and a doubling of endangered species.
- Marine benthic invertebrates are vital for ocean health but are increasingly impacted by human activities.
- There is often limited understanding of the implications of these impacts and inadequate provisions to contain them.
- Research and cooperation are still unbalanced among regions.
- Marine invertebrates are still poorly documented, particularly in the deep ocean and in the territorial waters of developing States and island States, which potentially host a high number of endemic taxa.
- Consistent funding for biodiversity monitoring is needed to prevent knowledge gaps from widening.
- Meaningful and ethical use of Indigenous knowledge and representation of early-career professionals are required.
- Seabed mining raises concerns about negative impacts, calling for coordination and cooperation between the Conference of the Parties to the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction and the International Seabed Authority (ISA).

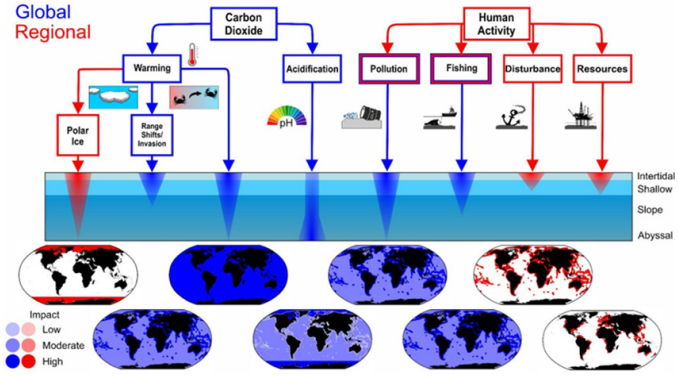
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1. Introduction

Since the publication of the second *World Ocean Assessment*, benthic species and habitats have been affected by human activities worldwide (figure I).

Benthic invertebrates are vital for ocean health and human well-being but are threatened by climate change, human activities (including bottom trawling) and pollution (including microplastics and contaminants).

Figure I
Effects of human activities on benthic species and habitats



Source: Prepared by the writing team.

2. Environmental change since the second *World Ocean Assessment*

Changes in overall status

Biodiversity

The World Register of Marine Species (WoRMS), as at 29 August 2024, held 246,517 valid marine species names, including 151,902 marine benthic invertebrates. Of all the new marine species discovered each year, about 60% are benthic invertebrates. From 2019 to 2023, of the 10,742 new marine species described, 7,252 (67.5%) were benthic invertebrates (figure II).

Of the 32 marine phyla with invertebrate species, 26 include benthic species (figure III). Among these, 21,271 species (14%) live at depths greater than 500 m.


Ellen Cuylaerts

Only 1.7% of marine benthic invertebrate species have been formally assigned to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (table 1). Most species (98.3%) have not been evaluated due to insufficient information.

According to WoRMS, the Ocean Biodiversity Information System, and the Marine Regions website (accessed Oct 2024), marine benthic invertebrates are found in all International Hydrographic Organization areas. However, significant regional variations reflect current knowledge gaps (figure IV).

Table 1
Number of marine benthic invertebrate species per category of the International Union for Conservation of Nature Red List of Threatened Species

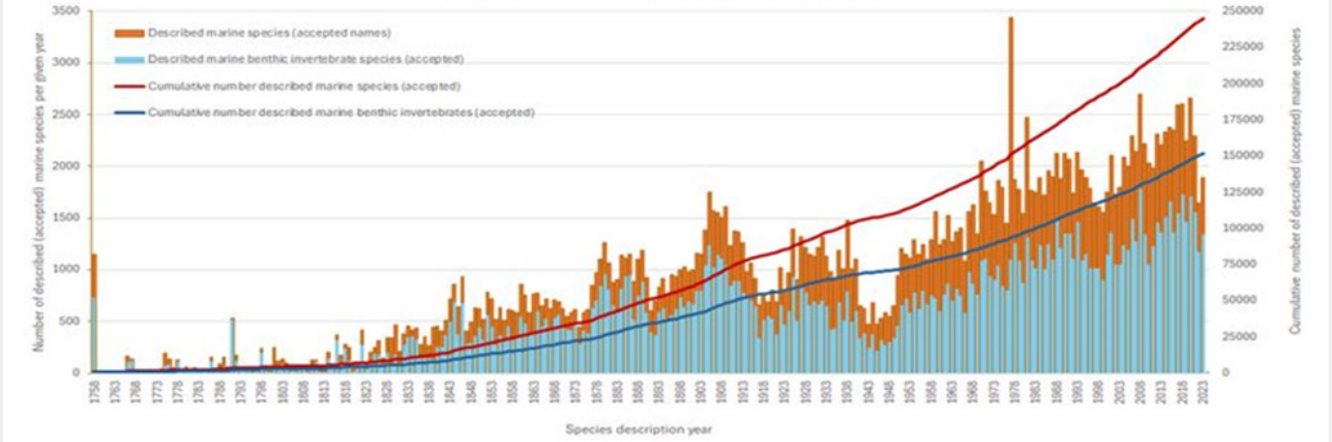
Red List category	Total number of marine invertebrate benthic species	
	1964–2018	2018–2023
Extinct	2	2
Critically endangered	18	91
Endangered	45	88
Vulnerable	237	292
Near threatened[a]	188	243
Least concern	1,104	1,184
Data deficient	624	657

Source: Prepared by the writing team.

[a] This number category includes four "conservation-dependent" species.

Figure II

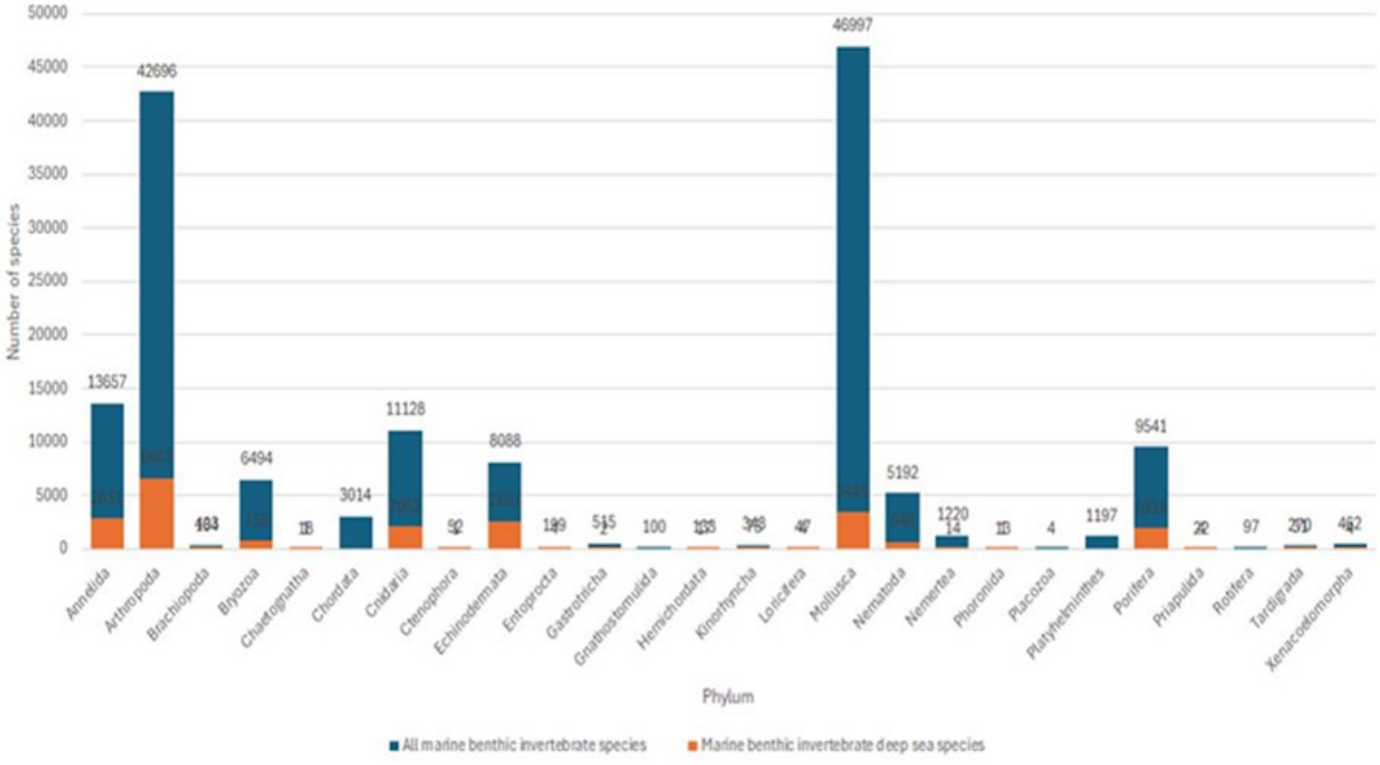
Global marine species discovery rate (accepted species only) since 1758



Source: Prepared by the writing team.

Figure III

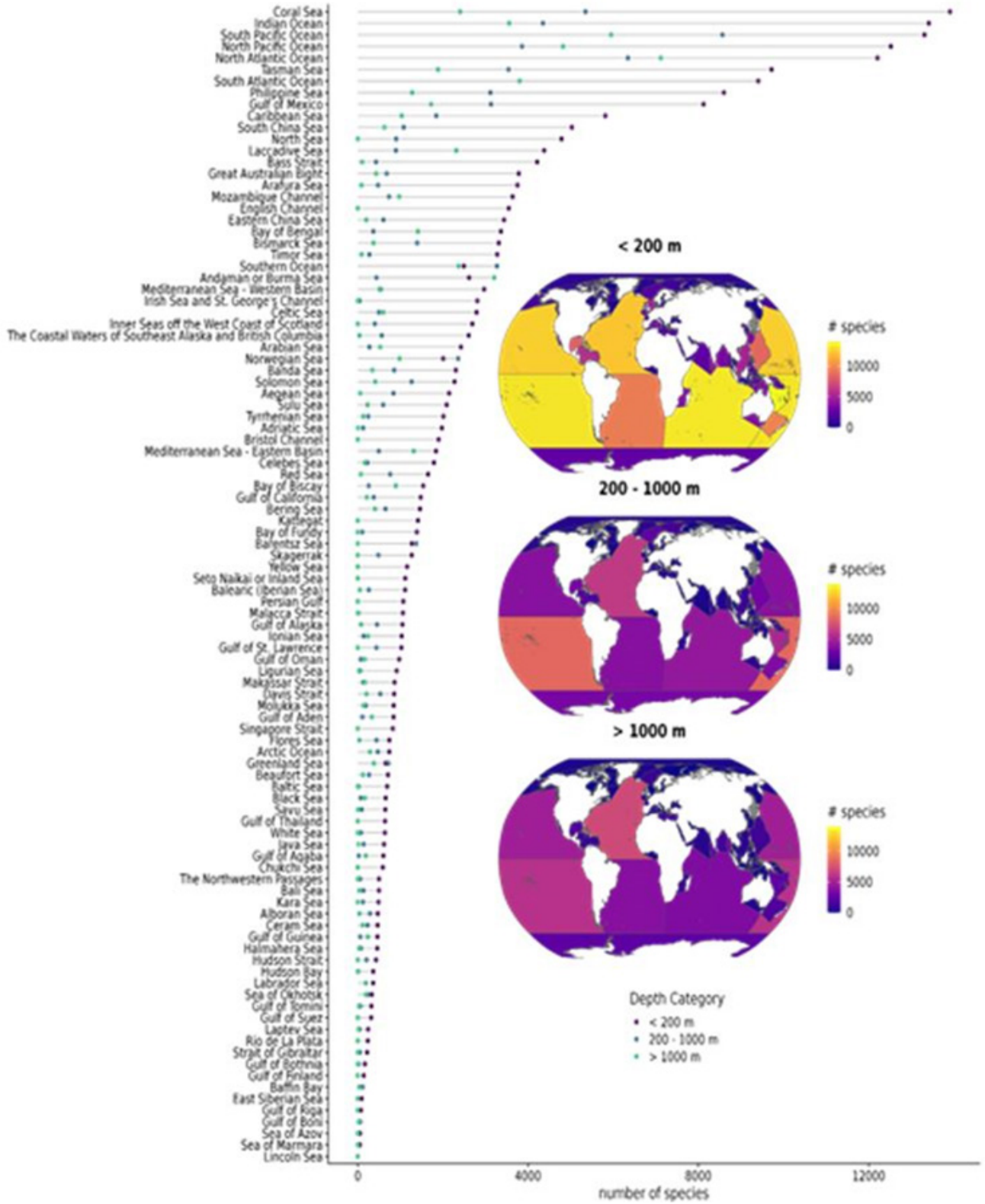
Global number of marine benthic invertebrate species, by group (phylum), showing total species numbers



Source: Prepared by the writing team.

Figure IV

Total number of recorded marine invertebrate benthic species for all International Hydrographic Organization sea areas for <200 m, 200-1000 m and >1000 m depth



Source: Prepared by the writing team.

Note: The boundaries of the International Hydrographic Organization sea areas follow Claus and others, 2014, and International Hydrographic Organization sea areas, version 3 (Flanders Marine Institute, 2024a), available online at www.marineregions.org (https://doi.org/10.14284/323). Species occurrences: Ocean Biodiversity Information System (OBIS), 2024. Species group information: WoRMS. Bathymetry data: European Marine Observation and Data Network (EMODnet), 2016; General Bathymetric Chart of the Oceans (GEBCO), 2015; and Provoost and Bosch, 2018.

Impacts of change on and interaction with other components of the marine system

Marine benthic ecosystems are crucial for ocean health and human well-being but are under growing pressure from human activities (Sweetman and others, 2017; Halpern and others, 2019; Gissi and others, 2021; Mamede, 2024) (table 2 and regional information).

Unprecedented environmental changes are causing range shifts, novel species assemblages and extirpations. Research and scientific guidance are essential for understanding ocean changes and their effects on benthic resources, ecosystem services and socioeconomic impacts, and for developing effective mitigation strategies (Griffiths and others, 2017; Schratzberger and Somerfield, 2020; Crespo and Pardal, 2022).

Table 2
Anthropogenic stressors and activities affecting benthic marine invertebrates and ecosystems worldwide

Human stressors and activities	References
Global warming and ocean acidification	Isla and Gerdes, 2019; Pineda-Metz and others, 2020; Venegas and others, 2023
Fishing, especially bottom trawling	Couce and others, 2020
Resource extraction, including mining and hydrocarbon exploitation	Henry and others, 2017
Bioinvasion by non-native species, including invasive, exotic	Zaiko and others, 2024
Marine- and land-based contaminants, including an estimated 3.05 million tons of microplastics in deep ocean sediments and perturbations caused by drifting plastic bags in the deepest ocean	Gao and others, 2022; Harris and others, 2023; Ribó and others, 2023; Shahnawaz and others, 2024; Jamieson and Onda, 2022
Oil spills	Goes and others, 2023
Urbanization	Momota and Hosokawa, 2021; Dreujou and others, 2023
Dredging and dumping	Prishchepenko and others, 2023; Neira and others, 2024
Offshore wind farms	Lloret and others, 2022
Anchor scour damage	Davis and others, 2023
Marine invertebrate interactions with harmful algal blooms and implications for One Health	Turner and others, 2021
Coastal defence and offshore structure installations	Wolanski and others, 2020

Source: Prepared by the writing team.

Contaminants and microplastics accumulate in the seabed, harming benthic invertebrates and ocean ecosystems (Mason and others, 2022; Ladewig and others, 2023). Widespread damage to benthic habitats and biodiversity affects marine ecosystem services in various ways across regions, highlighting the need for targeted seabed management (Wang and others, 2021; Lloret and others, 2022; Mamede, 2024).

Governance of the seabed within and beyond national jurisdiction

Deep seabed mining management has drawn significant attention from various stakeholders, including governments, research institutions, intergovernmental organizations, non-governmental organizations and the private sector. Concerns are focused on its harm to benthic invertebrates (Amon and others, 2022; Drazen and others, 2020; European Academies Science Advisory Council, 2023; Rabone and others, 2023; Stenvers and others, 2023; Sweetman and others, 2024) and inadequate management of seabed mining impacts (Picken and others, 2024). There have been calls by some for a moratorium, a precautionary pause or a ban (Deep Sea Conservation Coalition, 2024; World Wildlife Fund (WWF), 2024).

For the seabed outside of the national jurisdiction, the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction, once it comes into force, will provide management measures, including area-based management tools, such as marine protected areas (MPAs) and environmental impact assessments (Humphries and others, 2025) that could complement the existing measures for management of the seabed. To be effective, such management measures will require strong coordination and cooperation between the Conference of the Parties to the Agreement and ISA and regional fisheries management organizations (RFMOs) to ensure

the conservation and sustainable use of areas beyond national jurisdiction (Gottlieb and others, 2025). Furthermore, capacity-building and the transfer of marine technology in the Agreement that encompasses all of the substantive elements, including the fair and equitable sharing of benefits of marine genetic resources of areas beyond national jurisdiction, will help to reduce gaps in scientific knowledge and to support further management measures, which is essential, especially for developing countries. For areas within national jurisdiction, select regional seabed management aspects are summarized in table 3.

Table 3
Select examples of regional management of the seabed since 2019

Regions	Governance of the seabed
Arctic Ocean	**Central Arctic Ocean** The Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean entered into force in June 2021. The Agreement prevents the signatory countries from engaging in commercial fishing for 16 years and establishes a joint programme of scientific research and monitoring to further the understanding of ecosystems in an Arctic with retreating sea ice cover, as part of a long-term strategy to safeguard healthy marine ecosystems and ensure the conservation and sustainable use of fish stocks The entry into force on 17 January 2026 of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction may provide opportunities to address a legal gap wherein no existing legal instrument or body has the legal competence to designate area-based management tools, including MPAs, in portions of the central Arctic Ocean that lies in areas beyond national jurisdiction. **Barents Sea** Northward expansion of commercial bottom fish has increased the risk of bottom trawling damage to vulnerable benthic species and habitats in pristine, previously ice-covered areas in the Northern Barents Sea. In 2019, the Government of Norway agreed to close 443,000 km² of seabed to bottom-contact gear (Jørgensen and others, 2020). **Canadian Arctic** Conservation areas have been established to protect habitat-forming cold-water corals and sponges (CWCS) (DFO, 2024).
Baltic Sea, North-East Atlantic Ocean, Mediterranean Sea and Black Sea	**North Atlantic Ocean** While 18 benthic habitats are already the focus of status assessments in the maritime area of the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), remote and deepwater habitats remain understudied. Regulations concerning pollution or pressure and the creation of MPAs continue to be enacted across all regions. Currently, 10.8% of the OSPAR maritime area has been designated an MPA, but challenges remain with respect to generating sufficient ecological coherence (OSPAR, 2023). Green finance (e.g. nutrient, carbon or biodiversity credits) could provide the investment greatly needed for effective management and to support restoration at the seascape level (Preston and others, 2025).
South Atlantic Ocean and wider Caribbean	**South-West Atlantic** Cumulative impact assessment and conservation planning is under way to strengthen MPAs in the Brazilian exclusive economic zone (Magris and others, 2020). Marine spatial planning is ongoing in the Brazilian exclusive economic zone. **Africa (South Africa and Namibia)** In 2019, South Africa increased its MPA from 0.4% to 5% of its ocean territory through the implementation of 20 new MPAs (Sink and others, 2023). In South Africa and Namibia, trawl fisheries are receiving eco-certification, and routine benthic monitoring is carried out through commercial fishing activities. Enhanced mitigation measures are being undertaken for seabed damage caused by trawl fishing. Ecosystem-based management was identified as a suitable approach to effectively govern the most impactful human activities in marine systems (Skein and others, 2022).

Table 3 (*continued*)

Regions	Governance of the seabed
Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf	**Persian Gulf and the Sea of Oman** The Islamic Republic of Iran, Oman, Qatar and the United Arab Emirates have established MPAs to protect critical habitats. Bottom trawling restrictions, establishment of no-take zones within MPAs and seasonal fishing bans protect spawning seasons. National regulation targets have been introduced to reduce pollution from oil and chemical spills. The Regional Organization for the Protection of the Marine Environment is composed of the countries of the Cooperation Council for the Arab States of the Gulf, Iraq and the Islamic Republic of Iran. **Arabian Sea, Lakshadweep Sea and Bay of Bengal** MPAs have been introduced (for coral, seagrass and sea cucumbers), and fishing regulations and pollution control have been implemented. Marine resource management is supported by initiatives such as the Bay of Bengal Programme. Relevant national authorities enforce pollution-control measures and regulate scientific research activities. **Andaman Sea, Strait of Malacca and South China Sea** National regulations and conservation strategies are being implemented by Association of Southeast Asian Nations (ASEAN) countries through domestic laws and strategies (e.g. artificial reef). MPAs (marine park, no-take zone) are currently increasing in area. ASEAN countries are implementing, and have committed to further strengthening, measures to protect the marine environment and resources. Illegal, unreported and unregulated (IUU) fishing still happens. Overlapping laws and responsibilities between enforcement agencies create loopholes in enforcement. Issues with maritime borders create a grey area for enforcement when it comes to marine resources. **Bangladesh, India, Myanmar, Pakistan and Sri Lanka** Bangladesh (7.99% coverage), India (0.31%), Myanmar (0.48%), Pakistan (1.23%) and Sri Lanka (0.08%) have established MPAs to protect critical habitats such as corals, mangroves and seagrass. Bangladesh, India, Myanmar, Pakistan and Sri Lanka, as members of various regional organizations dedicated to environmental protection (ASEAN, South Asia Co-operative Environment Programme, Bay of Bengal Large Marine Ecosystem and Indian Ocean Rim Association), collaborate to address common maritime challenges. These include tackling pollution, combating piracy and developing joint conservation strategies to protect shared marine ecosystems. Fishing regulations, including seasonal fishing bans, are implemented.
North Pacific Ocean	**Various regions in the North Pacific** There are a number of recent conservation initiatives focused on preserving benthic biodiversity (e.g. Tang.ɢwan – ḥačxʷiqak – Tsi̱gi̱s MPA and glass sponge reef marine refuges in Canada; the Lianyungang Ganyu Wetlands and D̄ongling Tongzhou Bay intertidal zone in China; and the Muan tidal wetland protected area in the Republic of Korea).
South Pacific Ocean	**South-East Pacific** To achieve sustainable management of the marine resources in the South-East Pacific, coastal community harvest of benthic marine invertebrates must be included in data and reporting that inform fisheries management. In Chile and Peru, there is no authority to monitor community harvesting of benthic invertebrates or associated ecosystem impacts (Undersecretariat for Fisheries and Aquaculture of Chile (SUBPESCA), 2024; Marine Institute of Peru (IMARPE), 2024). New marine parks and associated management plans have been established in various parts of the South Pacific, including a large network around Australia, although only around 25% of it is fully protected.
Southern Ocean	**Antarctica** The Protocol on Environmental Protection to the Antarctic Treaty officially designates Antarctica as a ”natural reserve, devoted to peace and science”. The Commission for the Conservation of Antarctic Marine Living Resources is the international body responsible for the conservation of marine life and ecosystems in waters surrounding Antarctica.

Source: Prepared by the writing team.

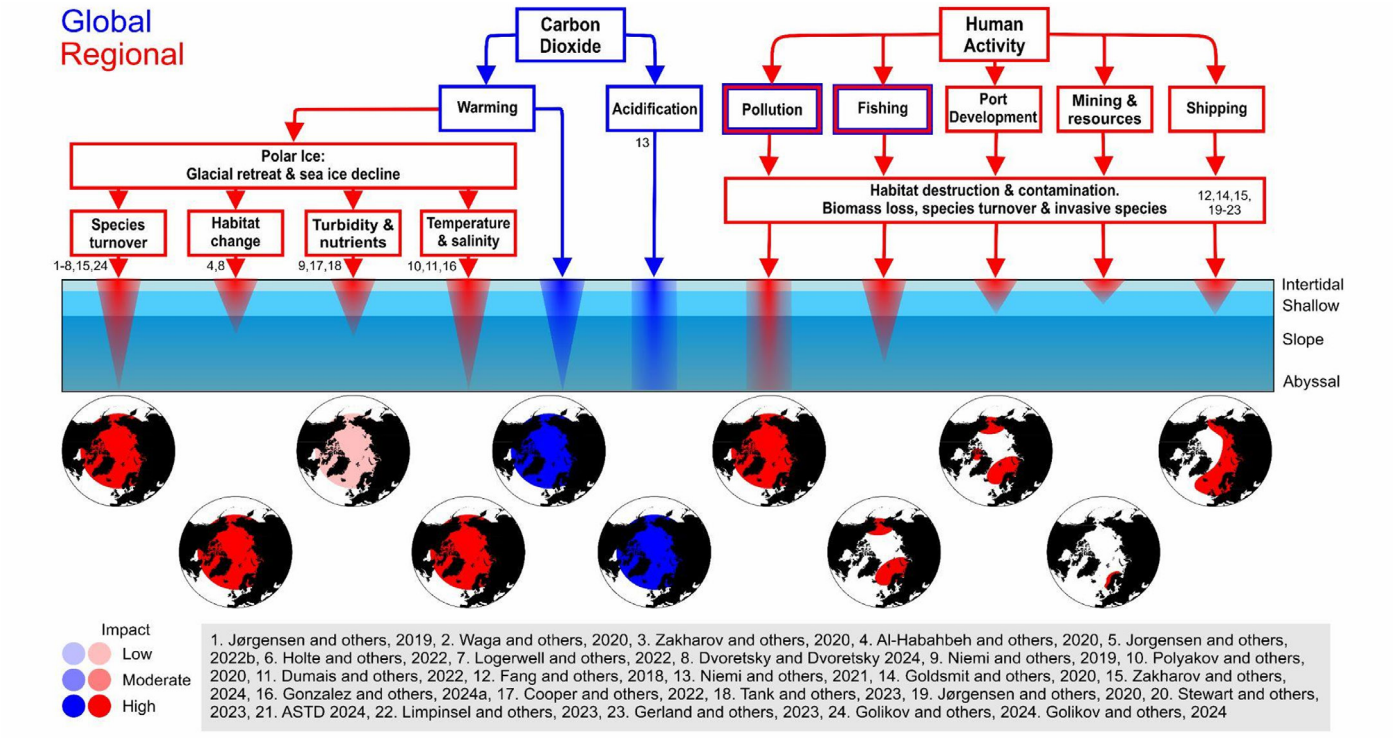
Region-specific changes

Arctic Ocean

The Arctic is an ecologically and culturally important marine region that remains largely untouched but is facing rapid environmental changes. Recent studies have established quantitative baselines of marine benthic biodiversity in previously underresearched areas (e.g. Azovsky and Kokarev, 2019; Pierrejean and others, 2020; Wei and others, 2020; Zakharov and others, 2020; Dumais and others, 2022; Gianasi and others, 2022; Vedenin and others; 2022, Bilous and others, 2022; Holte and others, 2022; Jacobs and others, 2022; Jørgensen and others, 2022a; Kenchington and others, 2022; Christie and others, 2023; McNicholl and others, 2024; Prozorkevich and others, 2024; Udalov and others, 2024). The Arctic faces major global and local threats such as warming, acidification, fishing, mineral extraction, port development and increased vessel traffic (figure V and citations therein). Microplastics are also a growing concern (Fang and others, 2018). Recent ecological changes include infaunal and epibenthic invertebrate population declines and species moving northward (e.g. Jørgensen and others, 2022b; Logerwell and others, 2022; Holte and others, 2022; Stewart and others, 2023; Gerland and others, 2023; Golikov and others, 2024). The status of commercially important crab and shrimp stocks varies from variable to healthy (Niemi and others, 2019; Gonzalez and others, 2024a). As the potential for commercial fishery expansion, new shipping routes and oil and gas extraction increases in the region, further mapping and monitoring efforts are necessary.

Figure V

Arctic Ocean: global and local stressors, associated pressures, and recently documented consequences for marine benthic invertebrates



Source: Prepared by the writing team.

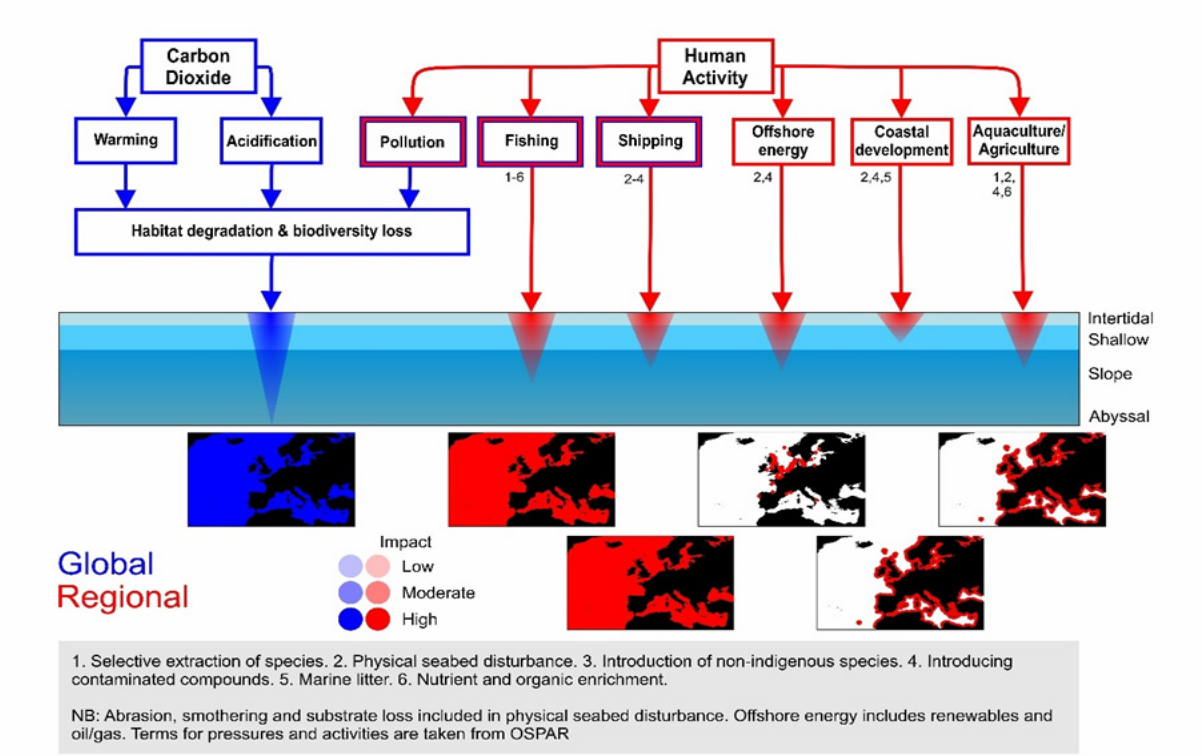
Note: Arrow width indicates relative importance of stressors at global and local scales.

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Except for oceanic ridges and hydrothermal vents, benthic habitats across subregions remain in poor status (Bevilacqua and others, 2020) with benthic diversity moderate or low for most subregions and none showing increases (OSPAR, 2024). Global warming affects habitats at all depths (Mediterranean Experts on Climate and Environmental Change (MedECC), 2020; see also figure VI). Fishing affects 48% of OSPAR-assessed areas via species extraction and seabed disturbance. Agriculture, aquaculture and tourism all drive nutrient enrichment, while green technologies increase contaminant inputs (Herbert-Read and others, 2022; OSPAR, 2024). Pressures disrupt ecosystem functions, exacerbate the effects of other stressors such as epizootic events (Katsanevakis and others, 2022) and compromise ecosystem services (Heckwolf and others, 2021). Benthic biodiversity improvements can benefit coastal communities through processes such as nutrient bioremediation (Watson and others, 2022).

Figure VI

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea: global and local stressors, associated pressures and recently documented consequences for marine benthic invertebrates



Source: Prepared by the writing team.

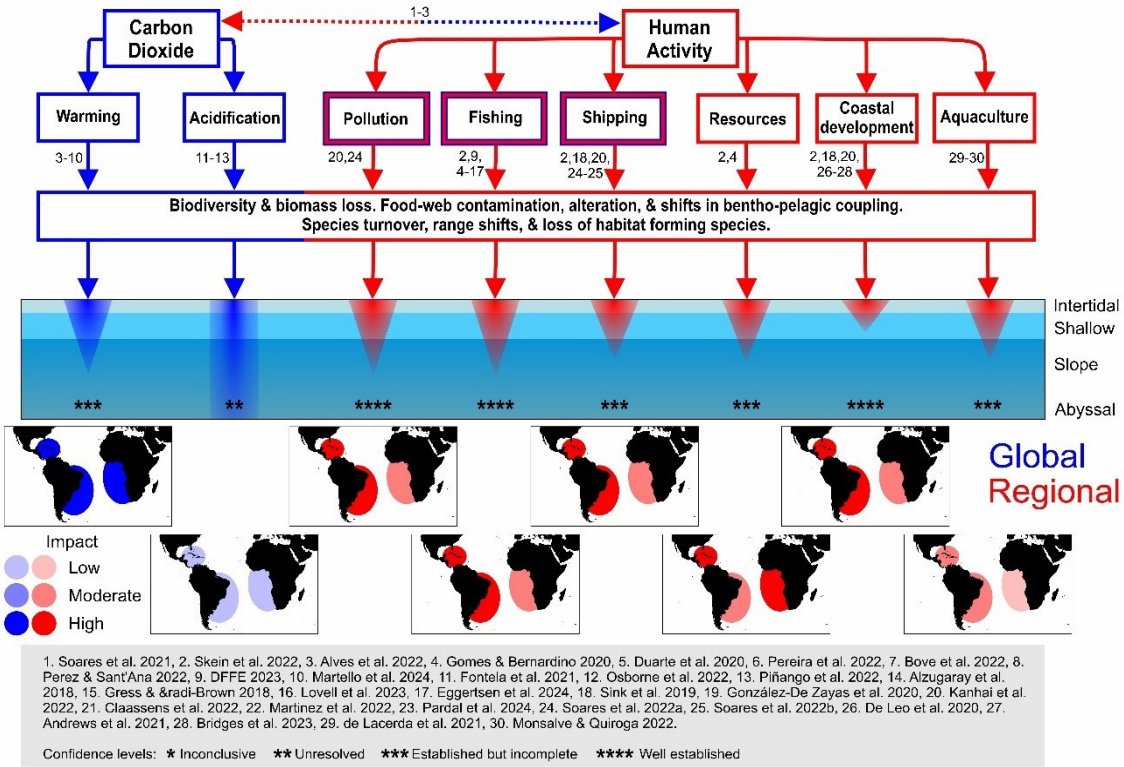
Note: Arrow width indicates relative importance of stressors at global and local scales.

South Atlantic Ocean and wider Caribbean

Despite limited and fragmented data, progress has been made. Research now focuses on deep environments, habitat mapping, identification of foundational species, and ecology (Sumida and others, 2020; Etnoyer and others, 2022). Changes have been noted in shallow habitats, including coral bleaching and mortality, shifts in benthic communities and commercially valuable invertebrate stocks, and the spread of non-indigenous species (NIS) (see figure VII and studies cited therein). Climate-driven physical changes increasingly affect benthic ecosystems. Local threats include fishing, coastal development, shipping, mining, aquaculture causing overexploitation, illegal fishing, pollution, bioinvasions and habitat damage (figure VIII). Shifts in fishery stocks also have significant socioeconomic impacts (Vögler and others, 2023; Engelhard and others, 2024). Considering the rapid changes under way, along with the potential expansion of the petroleum industry (Rodrigues, 2023), seabed mining (Bridges and others, 2023; Paiva and others, 2023), and the installation of offshore wind farms (Gorayeb and others, 2024), there is a need to expand the monitoring of benthic communities in this region, especially in deep habitats.

Figure VII

South Atlantic Ocean and wider Caribbean: global and local stressors, associated pressures and recently documented consequences on marine benthic invertebrates



Source: Prepared by the writing team.

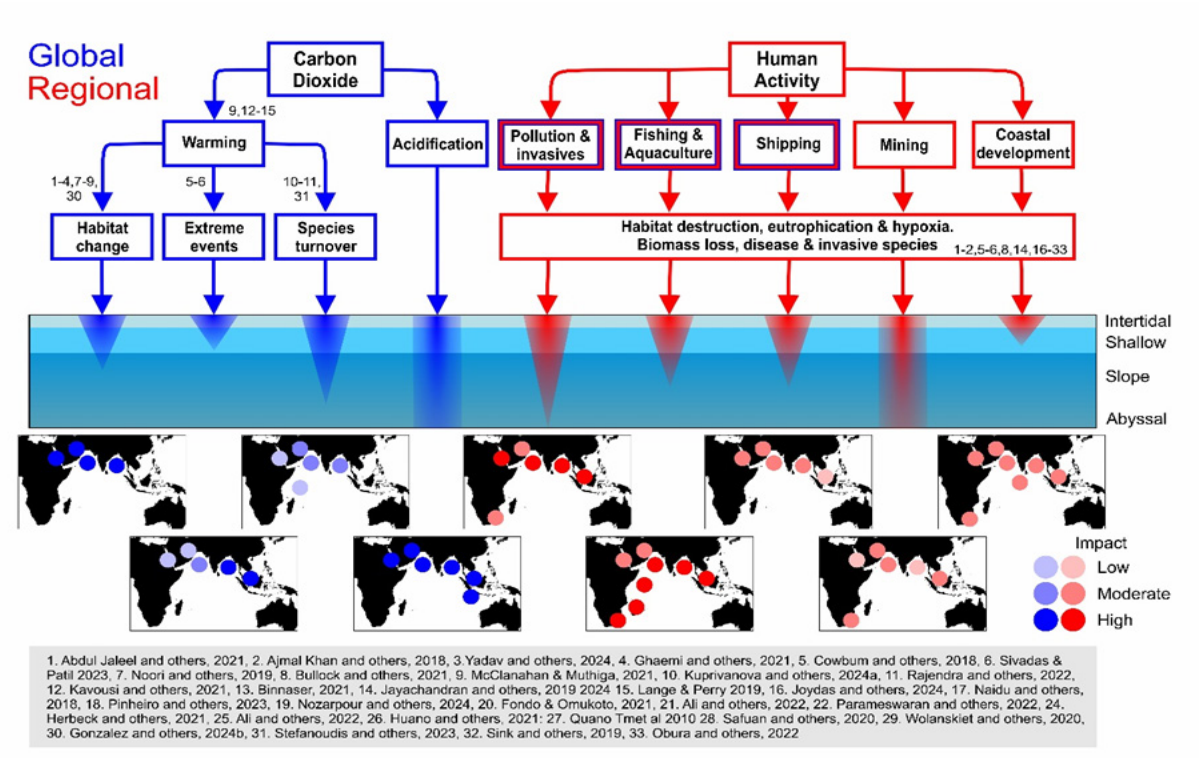
Note: Arrow width indicates relative importance of stressors at global and local scales.

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Multiple global and local stressors impact marine invertebrates in this region (figure VIII). Thermal stress causes coral bleaching and declines in abundance, even at depth (Diaz and others, 2023). Overfishing and destructive fishing practices degrade benthic habitats and threaten food security (Obura and others, 2022). Marine debris leads to marine life entanglement (Pattiaratchi and others, 2022), while oil spills and invasive species disrupt native biodiversity (Jayachandran and others, 2019, 2024; Huang and others, 2021). Coastal development and untreated wastewater discharge alter benthic communities (Sink and others, 2019) with prospective offshore mining likely to worsen impacts (Fennessy, 2024). Long-term studies on these pressures are limited (Sink and others, 2019), but new biodiversity surveys (such as Amjad and others, 2024) and ecological research provide insights into ecosystem resilience (Delfan and others, 2021; Stefanoudis and others, 2023). Functional ecology can help in the assessment of biodiversity roles and responses to environmental changes, while biogeography and metacommunity ecology can help to identify large-scale patterns and habitat connections for conservation planning. Experimental research can provide information on how marine invertebrates respond to natural variability, climate change and pollutants. Key ecosystem services at risk include food security through fisheries, coastal protection and tourism (United Nations Environment Programme–National Center for Wildlife (UNEP-NCW), 2024; Nairobi Convention and WIOMSA, 2025).

Figure VIII

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf: global and local stressors, associated pressures and recently documented consequences for marine benthic invertebrates



Source: Prepared by the writing team.

Note: Arrow width indicates relative importance of stressors at global and local scales.

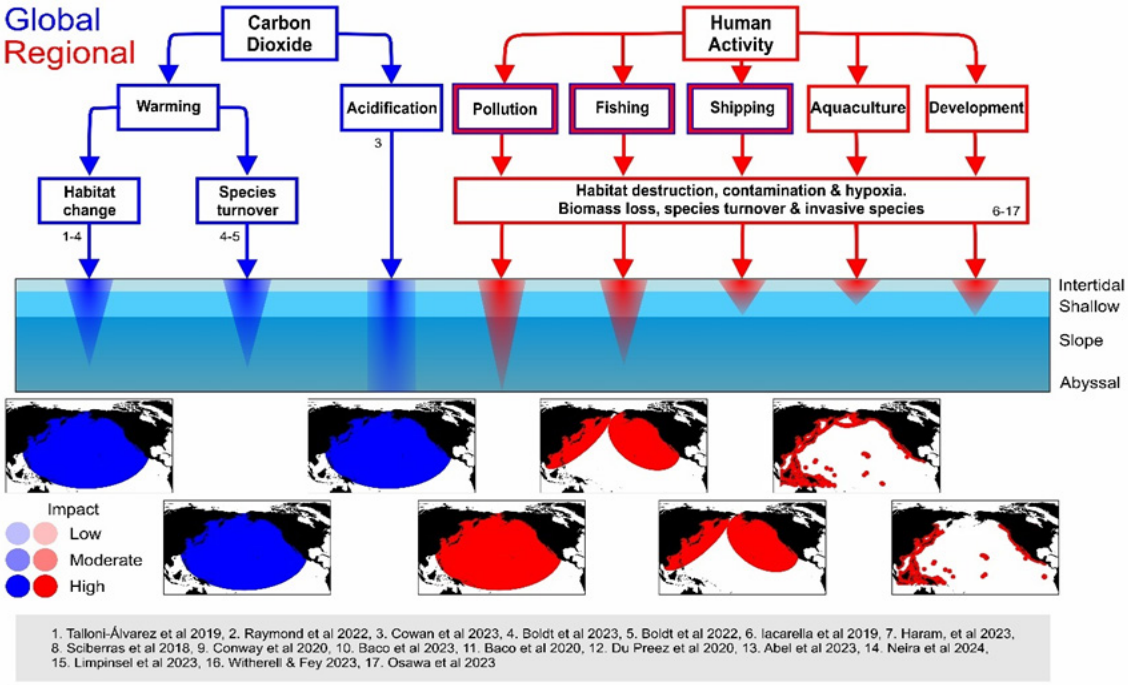
North Pacific Ocean

Ocean temperatures have increased over the long term (Talloni-Álvarez and others, 2019; Guo and others, 2020; Chen and others, 2020; Boldt and others, 2022, 2023; Alma and others, 2023; Cowan and others, 2023; Han and others, 2023), leading to widespread intertidal die-offs from heatwaves and hypoxia (Raymond and others, 2022; Chen and others, 2020; Hesketh and Harley, 2023), species turnover, range shifts and the spread of invasive species (Buser, 2023; Wang and others, 2019, 2023; Hu and others, 2021; Xu and others, 2020, 2023, 2024; Drinkwin and others, 2019). The Puget Trough and the Piip volcano are hotspots of seafloor biodiversity in the North Pacific (Wei and others, 2020; Rybakova and others, 2023) (figure IX).

Trawl fisheries are a major fishery type in the region (Morgan and Baco, 2021). Many invertebrate stocks, including crabs, oysters, geoduck, Pacific oysters and northern abalone, have declined across the North Pacific, with severe losses species such as the Bering Sea snow crab (Szuwalski and others, 2023). Aquaculture faces challenges from ocean acidification, hypoxia, temperature anomalies and invasive species (Alma and others, 2023; Cowan and others, 2023; Qu and others, 2024). In 2021, a sea star outbreak in the Jiaozhou Bay in China caused major damage to shellfish farming and fisheries.

Figure IX

North Pacific Ocean: global and local stressors, associated pressures and recently documented consequences for marine benthic invertebrates



Source: Prepared by the writing team.

Note: Arrow width indicates relative importance of stressors at global and local scales.

South Pacific Ocean

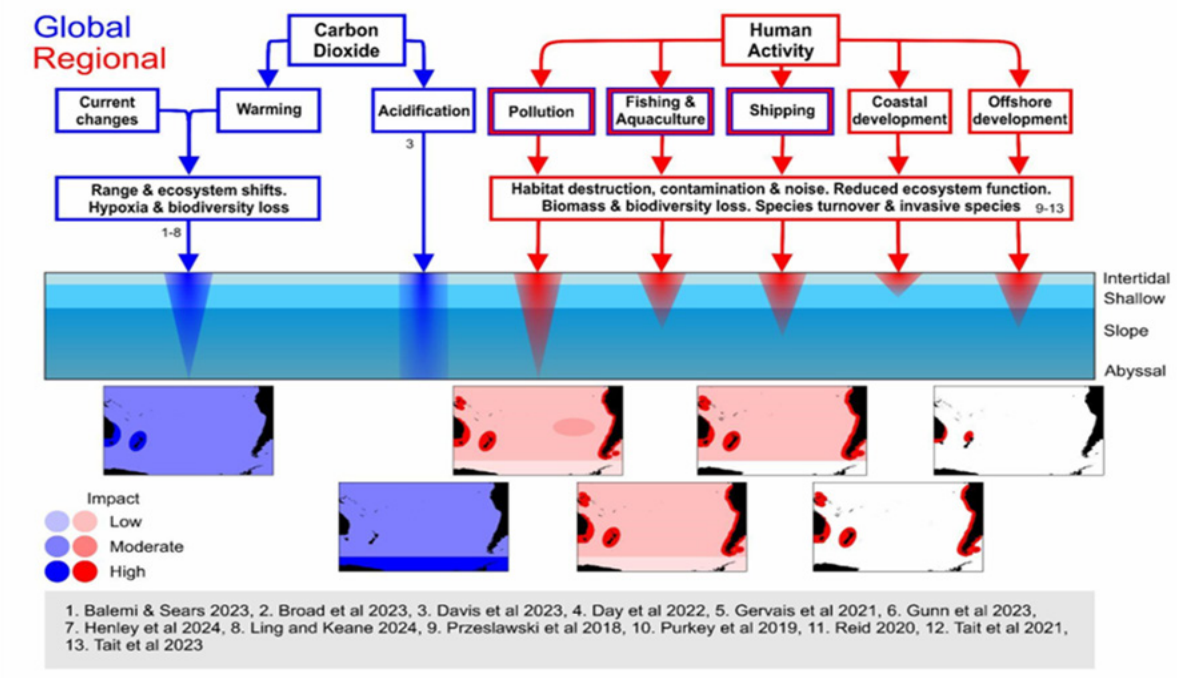
Deep-sea biodiversity of the South Pacific has recently expanded through taxonomic discoveries on the south-eastern Australian slope and abyss (Gunton and others, 2021; O'Hara and others, 2020) by means of, inter alia, species inventories (Kupriyanova and others, 2024a), the discovery of new species (Flaxman and Kupriyanova, 2024; Wu and others, 2021; Blake, 2023; Gunton and others, 2023; Georgieva and others, 2023; Zhang and others, 2020) and taxonomic revisions (Zhang and others, 2019). Underwater imagery and samples from the Coral Sea have provided new data on black corals (Horowitz and others, 2022), carnivorous sponges (Ekins and Hooper, 2023) and mesophotic reefs (Huang and others, 2024).

Warming waters have caused range shifts of benthic invertebrates across the region (Davis and others, 2023; Gervais and others, 2021), leading to ecosystem changes, especially in photic zones, such as kelp gardens shifting to urchin barrens (Ling and Keane, 2024; Balemi and Shears, 2023).

Warming waters and marine heatwaves (figure X) have reduced key habitat for marine invertebrates, such as giant kelp forests (Tait and others, 2021) and coral reefs (Henley and others, 2024), including through repeated bleaching events around Lord Howe Island, the world's southernmost coral reef (Moriarty and others, 2023). In Australia, extreme flooding, bushfires and heatwaves have been associated with freshwater plumes, sedimentation, turbidity and high temperatures, all of which have been shown to negatively impact certain benthic invertebrates (Larkin and others, 2024; Glasby and others, 2023; Barros and others, 2022).

Figure X

South Pacific: global and local stressors, associated pressures and recently documented consequences for marine benthic invertebrates



Source: Prepared by the writing team.

Note: Arrow width indicates relative importance of stressors at global and local scales.

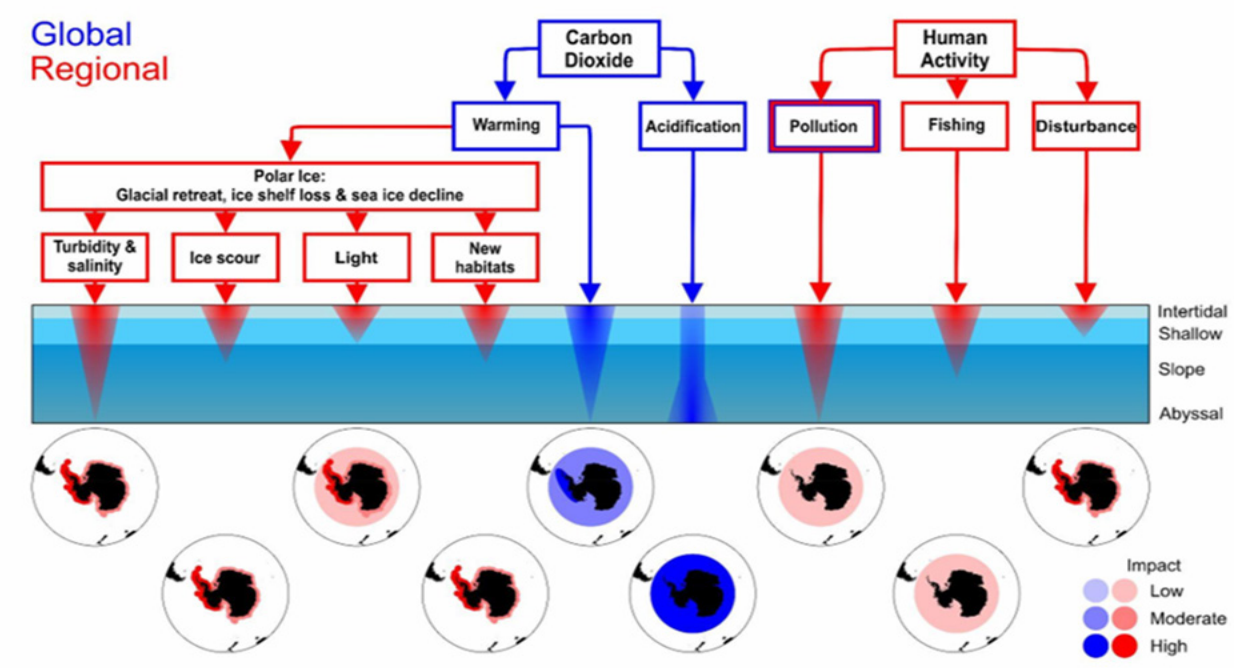
Southern Ocean

The ecosystems of Antarctica host a diverse, highly endemic community shaped by isolation and freezing temperatures. Projected changes (figure XI) will likely reach tipping points in physiological limits, primary productivity, ecosystem function and competition by the end of this century (Griffiths and others, 2024). These changes will affect Antarctic benthic ecosystem health, stability and uniqueness as endemic cold-water species decline and cosmopolitan species move south. Benthic changes remain poorly understood, with research focused mostly on a few shallow-water taxa, requiring advanced technologies to address geographic, depth, seasonal and taxonomic gaps (Griffiths and others, 2024).

Cold-adapted species face threats from local and global drivers, including warming, acidification and changes to the cryosphere. The impacts vary by location, depth and community type, with the most significant changes observed in the shallows of the West Antarctic Peninsula (Griffiths and others, 2024). These include the emergence of newly exposed coastline (leading to new habitats), reduced sea ice and increased iceberg scouring and turbidity, leading to higher mortality, lower diversity and reduced primary production, carbon storage and spatial competition (Griffiths and others, 2024).

Figure XI

Southern Ocean: global and local stressors, associated pressures and recently documented consequences for marine benthic invertebrates



Source: Prepared by the writing team.

Note: Arrow width indicates relative importance of stressors at global and local scales.

3. Implications for achieving the targets of the Sustainable Development Goals of the 2030 Agenda for Sustainable Development

The preservation and sustainable management of marine ecosystems, a key focus of the Sustainable Development Goals, is closely tied to benthic fauna, which are crucial for ecosystem health and resilience. This connection is particularly evident in Goal 14, which is aimed at conserving and sustainably using the oceans, seas and marine resources. The conservation of benthic fauna also supports Goal 13 (climate action) and Goal 15 (life on land), as healthy marine ecosystems help to regulate the climate and maintain global ecological balance.

The negative biodiversity and ecosystem trends outlined in the present subchapter hinder progress towards the achievement of relevant Goals. Effective implementation of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction to complement existing management measures and strengthened ocean management at the regional and national levels is crucial for advancing Goal 14. Increasing conservation-focused ocean management measures at the regional and national levels can support the achievement of Goal 14, contributing to addressing climate change (Goal 13) and reducing biodiversity loss (Kunming-Montreal Global Biodiversity Framework).

4. Key remaining knowledge and capacity gaps

(a) Marine invertebrates are underdocumented in the deep ocean, developing States and island States, and there are few experts on certain taxa.

(b) Increased digitization and genomic research are needed to identify cryptic species, integrate species information and improve accessibility.

(c) Documenting larval and juvenile settlement in deeper ecosystems remains challenging.

(d) Research on the biological pump and human impacts is needed.

(e) Local research and cooperation need improvement:

  (i) To activate skills and resources to use citizen and community science programmes to fill knowledge gaps;

  (ii) To develop effective succession planning and career development opportunities for early and mid-career marine scientists;

  (iii) To meaningfully and ethically consider Indigenous Peoples and First Nations and local knowledge;

  (iv) To secure consistent funding for long-term biodiversity monitoring.

(f) The recording of benthic invertebrates during assessments of commercial fisheries using bottom trawl should be used as a supplement to small-scale grab or underwater video methods.

(g) Ocean digital twins should be developed that compile available data and allow the development of future scenarios and predictions.

(h) Imaging techniques, possibly combined with artificial intelligence, can be used to monitor infrequently assessed, remote and inaccessible benthic ecosystems.

(i) Improved seabed management in relation to increasing human activities is needed.

(j) Networking across regions and disciplines is vital for understanding marine biodiversity, gathering key information, monitoring changes and conducting research on biodiversity patterns and processes, improving the societal relevance of research (Tolochko and others, 2021).

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Subchapter 4D
Fishes

Key points

- The accelerating impacts of climate change continue to affect fish life histories and populations globally.
- Since the publication of the second *World Ocean Assessment*, 787 new species of fish have been added to the FishBase database, which contains a total of 35,002 species described.
- New or improved research techniques, such as satellite tagging, video cameras and molecular genetic work, are helping to advance understanding of fish diversity, behaviour and biology.

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1. Introduction

The present subchapter provides an update on the taxonomy, biology, distribution, habitat and conservation status of bony (Osteichthyes) and non-bony (Chondrichthyes and Agnatha) fish. It is focused on the period 2018 to 2023, on what changes have occurred globally and regionally in terms of production and diversity and on new information that has become available since the publication of the second *World Ocean Assessment*. The present subchapter will also contain a discussion of remaining key knowledge gaps, capacity changes to better understand fish and whether any new gaps have come to light.

Other overlapping or complementary information relevant to fishes, including changes to fish biomass, is provided in the subchapters on large- and small-scale fisheries (subsect. 5A, subchaps. 1A and 1B); recreational fishing (subsect. 5A, chap. 2); climate change (sect. 4, chap. 1); specific fish habitats (sect. 4, chap. 5, and various subchapters); physical conditions and cumulative pressures (sect. 4, chaps. 3 and 6); and the socioeconomic importance of fish and how fish fit into One Health (subsects. 5A and 5B, various chapters).

2. Environmental change since the second *World Ocean Assessment*

Fish biomass is strongly affected by environmental, anthropogenic, global and regional pressures. Climate change and the resulting impacts on the marine environment (see sect. 4, chaps. 1 and 3) are having a significant effect on fish populations globally, from positive expansion and growth in new areas (e.g. polar and high-latitude areas) to significant declines in other areas (Nagelkerken and others, 2023; Blanchard and Novaglio, 2024). These pressures also affect fish biology and growth, fish behaviour, the timing of spawning and migration, and natural mortality (Nagelkerken and others, 2023). Many regions are affected by the removal of fish by poorly managed fishing and fisheries (subsect. 5A, subchaps. 1A and 1B and chap. 2), including through habitat damage from fishing gear, illegal, unreported and unregulated (IUU) fishing and the arrival or introduction of alien species.

The latest reports of the Intergovernmental Panel on Climate Change (IPCC) and the Food and Agriculture Organization of the United Nations (FAO) have projected range shifts among marine fish, suggesting latitudinal changes in fish biomass and decreasing biodiversity (Cooley and others, 2022). Most areas in lower latitudes are projected to have decreasing fish biomass into the future due to unfavourably warm ocean temperatures, while high-latitude areas are expected to have increased fish biomass as a result of more favourable warm temperatures (Blanchard and Novaglio, 2024).

Climate change is also increasing spatiotemporal life history mismatches, such as in larval access to food sources (Nagelkerken and others, 2023). Non-climate, anthropogenic factors amplify the impacts of climate change (Gissi and others, 2021).

The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction may support habitat protection and management of fishing in high-seas areas, which will in turn support fish populations and biodiversity (Wang 2025; Santos and others, 2022).

Continuous research and documentation of the spatial biodiversity and International Union for Conservation of Nature (IUCN) status of fish have advanced in recent years (tables 1 and 2). A total of 787 new species have been described in FishBase (table 1) and 6,062 have been assessed by IUCN (table 2) since 2019.

Table 1

Number of described marine species of fishes in different habitats across taxonomic class, including species identified since 2019

HABITAT	Class: Teleostei – Described since 2019	Teleostei – All species (2024)	Elasmobranchii – Described since 2019	Elasmobranchii – All species (2024)	Holocephali – Described since 2019	Holocephali – All species (2024)	Coelacanthi – Described since 2019	Coelacanthi – All species (2024)	Total species identified, by habitat (percentage of all identified fish)
Bathydemersal	38	1 900	9	327	2	52	–	–	2 279 (6.5)
Bathypelagic	14	1 399	1	36	–	–	–	2	1 437 (4.1)
Benthopelagic	234	11 546	5	169	–	–	–	–	11 715 (33.5)
Demersal	225	11 448	19	480	–	3	–	–	11 931 (34.1)
Pelagic	48	1 196	–	1	–	–			1 197 (3.4)
Pelagic-neritic	48	917	1	36	–	–	–	–	953 (2.7)
Pelagic-oceanic	9	406	3	86	–	–	–	–	492 (1.4)
Reef-associated	130	4 890	1	108	–	–	–	–	4 998 (14.3)
Total (percentage of all identified species)	**746** –	**33 702 (96.3)**	**39** –	**1 243 (3.6)**	**2** –	**55 (0.2)**	**0** –	**2 (<0.1)**	**35 002**

Source: Prepared by the writing team.

Table 2

Number of marine fish species in each International Union for Conservation of Nature category across taxonomic classes, including the number newly assessed since the drafting of the second *World Ocean Assessment* (2019)

IUCN CATEGORY	Class: Teleostei – Assessed since previous *World Ocean Assessment* (2019)	Teleostei – Total (2024)	Elasmobranchii – Assessed since previous *World Ocean Assessment* (2019)	Elasmobranchii – Total (2024)	Holocephali – Assessed since previous *World Ocean Assessment* (2019)	Holocephali – Total (2024)	Coelacanthi – Assessed since previous *World Ocean Assessment* (2019)	Coelacanthi – Total (2024)	Total fish species by IUCN category (percentage of all IUCN-assessed species)
Least concern	3 685	9 262	345	503	20	35	–	–	**9 800 (74.2)**
Near threatened	37	113	102	119	4	4	–	–	**236 (1.8)**
Vulnerable	63	235	160	171	4	4	–	1	**411 (3.1)**
Endangered	43	95	114	124	–	–	–	–	**219 (1.7)**
Critically endangered	10	21	88	92	–	–	–	1	**114 (0.9)**
Extinct in the wild or extinct	–	1	1	1	–	–	–	–	**2 (< 0.1)**
Data deficient	1 311	2 281	66	137	9	10	–	–	**2 418 (18.4)**
Total	**5 149**	**12 008**	**876**	**1 147**	**37**	**53**	**0**	**2**	**13 210 (100)**

Source: Prepared by the writing team.

3. Region-specific changes

Arctic Ocean

Arctic fish populations are experiencing significant shifts in spatial distribution, population dynamics and community composition due to climate change, overfishing and environmental changes. The warming Arctic Ocean is driving the poleward migration of sub-Arctic species such as Atlantic cod (*Gadus morhua*), altering the composition of marine ecosystems (Gordó-Vilaseca and others, 2024). Concurrently, the retreat of sea ice is enabling increased fishing pressure in previously inaccessible areas, raising concerns for vulnerable species such as polar cod (*Boreogadus saida*) (Bryndum-Buchholz and others, 2019; Steiner and others, 2021). Invasive species and the expansion of commercial fisheries are compounding the pressures on endemic Arctic fish populations (Ogorelec and others, 2022). The cumulative effects of these changes threaten the sustainability of key species and the broader Arctic marine food web, necessitating adaptive management strategies (Bluemel and others, 2022; Nilsen and others, 2022). Recent studies emphasize the importance of implementing spatial fisheries management and establishing marine protected areas (MPAs) to mitigate these impacts (Phillips and others, 2025), including through meaningful partnerships and collaborations with local and Indigenous Arctic communities. These measures are crucial for preserving Arctic biodiversity and ensuring the long-term viability of commercial fish stocks in the region (Gordó-Vilaseca and others, 2024).

North Atlantic Ocean, Baltic Sea and North Sea

Climate change is expected to increasingly affect fish populations in the northern oceanic waters. Atlantic water temperatures are projected to increase, reducing sea ice extent and boosting primary productivity, influencing distribution, growth rates, spawning locations and early-stage mortality of fish species (Gordó-Vilaseca and others, 2024). There has been a shift in the ranges of North Atlantic species moving eastward and warmer-water species migrating north, leading to an enrichment of Arctic and sub-Arctic marine fauna (Gordó-Vilaseca and others, 2023). These waters face decreasing biomass and biodiversity with respect to traditionally high-latitude sedentary species (Gordó-Vilaseca and others, 2024). In more southern areas (such as the Canary Islands region), there is a tropicalization of fish populations, where many new species of tropical origin are increasingly being reported (Bañón and others, 2024; Falcón and others, 2023), and northward expansion of common species off north-western Africa (such as *Scomber colias* and *Sardinella aurita*) have been reported (Amenzoui and Baali, 2018; Blanchet and others, 2019; International Council for the Exploration of the Sea (ICES), 2021). The patterns of change are highly variable from location to location depending on the rapidity of change; for example, rapidly warming locations develop more rapidly growing fish and slow-changing areas have more slow-growing species (Receveur and others, 2024).

Mediterranean Sea and Black Sea

The Mediterranean Sea is a hotspot of cumulative climate change impacts and is subject to increasing heatwaves, extreme events, seasonal warming and changes in currents and degree of stratification (Hidalgo and others, 2018). These developments are causing changes to fish ranges, spawning seasons (Moltó and others, 2024), population structures, dispersal patterns, the structure of food webs and the composition of communities, as well as the increasing presence of non-endemic species (Zenetos and Galanidi, 2020; Yapici, 2021).

There is strong biogeographical structuring of populations, with many examples in northern areas showing northward displacements (e.g. Sbragaglia and others, 2020), but fish populations are also responding unexpectedly to change in more intermediate latitudes with southward distributional shifts of demersal species (Sanz-Martín and others, 2024; Sbragaglia and others, 2020). There is an east-west gradient in warming and increasing immigration of species from the Red Sea and Indian Ocean, making the eastern Mediterranean a hotspot of invasive species (Öztürk, 2021).

Anthropogenic disasters, such as the explosion of the Kakhovka Dam in 2023, are expected to significantly worsen the ecological state of the Black Sea (Minicheva and others, 2023; Vyshnevskyi and others, 2023), although some large pelagic species (bluefin tuna and swordfish) are slowly returning to the Black Sea for unclear reasons (Di Natale and others, 2019; Di Natale, 2021).

South Atlantic Ocean and wider Caribbean

The South Atlantic Ocean and Caribbean Sea have undergone significant changes since 2018, including warming trends and salinity alterations (Chidichimo

and others, 2023; Craig and others, 2021), as well as increased extreme events (Gramcianinov and others, 2023). These changes are having significant effects on marine ecosystems, including shifts in the distribution of species (e.g. tropical species, tuna) and impacts on biodiversity (Perez and Sant'Ana, 2022; Townhill and others, 2021; Craig and others, 2021). Coral reefs in some areas have been dying from disease and bleaching, resulting in the loss of reef fish habitat and changes in fish communities (Swaminathan and others, 2024; Reimer and others, 2024).

Indian Ocean

The Indian Ocean region is known for its exceptional biodiversity, driven by a unique monsoon system that drives upwelling, nutrient-rich currents and high primary productivity (Marsac and others, 2024). Estimates of fish diversity report over 3,600 species of coastal fishes in the western Indian Ocean (Bullock and others, 2021). The region is also increasingly experiencing rapid sea surface warming, leading to deoxygenation in some coastal areas of the Arabian Sea and the Bay of Bengal (Dalpadado and others, 2023), contributing to biodiversity loss. Large fish biomass reductions (over 50%) have been projected, with tunas being particularly affected (Wilson and others, 2021), although bluefin tuna have expanded their distribution range (Di Natale and others, 2022). Hotspots of threatened species have been identified in the southern Red Sea and the southern coast of India, with more than 90% of such species being affected by targeted fisheries, caught as by-catch, and affected by IUU fishing activities, which is particularly the case for valuable species, including sharks and tunas (Bullock and others, 2021; Worm and others, 2024).

North Pacific Ocean

The North Pacific features the highest number of fish species and the most genetic diversity globally, owing to its large latitudinal scale and diversity in marine habitats and ocean currents. The area includes Arctic to tropical waters and highly biodiverse areas such as the Coral Triangle and oceanic islands and archipelagos (Manel and others, 2020; Miller and others, 2018; Tittensor and others, 2010). Mesophotic zones around tropical coral reefs harbour high fish diversity (Pinheiro and others, 2019).

Climate change is increasing poleward shifts in teleost and elasmobranch distributions and fish invasions and extinctions, particularly in oceanic islands (Cruz and others, 2024; Hastings and others, 2020; Tanaka and others, 2021). Increasingly frequent and intense marine heatwaves are likely to drive marine fish extinctions in Pacific islands, potentially affecting future food security (Asch and others, 2018; Jacox and others, 2020; Smale and others, 2019; Oliver and others, 2021). The effects of climate change, El Niño and La Niña are expected to redistribute tuna species (Lehodey and Senina, 2018).

South Pacific Ocean

The diversity of fish in the South Pacific, including tropical, subtropical and temperate regions, faces increasing threats from climate change, pollution and overexploitation (Clarke and others, 2020; Dulvy and others, 2021; O'Hara and others, 2021). Warming oceans are shifting distributions polewards and are predicted to alter patterns of migration and invasion and potentially cause extinctions (Rodriguez-Burgos and others, 2022; Clarke and others, 2020). The El Niño/Southern Oscillation affects fish diversity and distribution and is forecast to increase in frequency and intensity (Oliver and others, 2021). Marine heatwaves in 2023/24 triggered the fourth global coral bleaching event, spreading across the Australian Great Barrier Reef and South Pacific islands, but the impacts on fish biodiversity are still unclear (Reimer and others, 2024). Microplastic ingestion in marine fish, including commercial species in South Pacific coastal regions and oceanic islands, is rising, but population-level impacts have not been assessed (Muñoz-Pérez and others, 2023; Savoca and others, 2021; Wootton and others, 2021).

Southern Ocean

Antarctic fish populations are increasingly affected by climate change, marine heatwaves, fishing pressures and environmental shifts. Warming waters in regions such as the Antarctic Peninsula are disrupting reproductive cycles of species such as black rockcod (*Notothenia coriiceps*) and causing habitat loss for ice-dependent species such as emerald rockcod (*Trematomus bernacchii*) and yellowfin icefish (*Chaenocephalus aceratus*) (Novillo and others, 2024). Reduced sea ice is severely affecting Antarctic silverfish (*Pleuragramma antarcticum*), a key prey species, especially along the western Antarctic Peninsula (Caccavo and others, 2021). Fishing pressures in areas such as the Ross Sea exacerbates these challenges, particularly for top predators such as Antarctic toothfish (*Dissostichus mawsoni*), which play a critical role in the ecosystem (Caccavo and others, 2021). Recent studies highlight the vulnerability of Antarctic lanternfish (*Electrona antarctica*), as changes

in prey availability and oceanographic conditions alter their feeding strategies (Duan and others, 2024). Adaptive management strategies, such as those implemented through the Commission for the Conservation of Antarctic Marine Living Resources, are crucial to mitigating these impacts and preserving Antarctic marine ecosystems (Corso and others, 2024). Conservation efforts are critical as climate change effects intensify, which will in turn increase the need for continued research and monitoring (Greco, 2022).

4. Key remaining knowledge and capacity gaps

Key gaps in the current understanding of marine fish and steps to reduce those gaps are listed in tables 3 and 4.

Table 3
Key gaps in the second *World Ocean Assessment* and recent efforts to reduce those gaps

Knowledge and capacity gaps	Recent steps taken to address the gaps
Taxonomic and biosystematics infrastructure and capacity	The FAO ecosystem approach to fisheries (EAF)-Nansen Programme is providing a ship and research support staff to train students and scientists in coastal developing countries.
Mobilization of existing data into open global repositories	Creation of the Global Biodiversity Information Facility (GBIF) (GBIF, 2024) to obtain data from samples not examined (e.g. from scientific surveys).
Understanding of mesopelagic and deep-sea fish diversity	European marine strategies include implementation of programmes for monitoring of deep-sea habitats.
Cumulative stressors on fish	In resolution 7.2 of the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals (Rev.COP14), cumulative stressors on migratory species, including fish, are identified and the need for action is emphasized in that regard.

Source: Prepared by the writing team.



Table 4
New gaps identified since the publication of the second *World Ocean Assessment*

New knowledge and capacity gaps	Steps taken to address the gaps
Detection of IUU fishing	Improved satellite monitoring of vessels (e.g. by Global Fishing Watch).
Satellite surveillance	Satellite monitoring has improved for the tracking of illegal fishing, pollution and maritime traffic, providing real-time data (Matley and others, 2024; Paolo and others, 2024). Electronic devices (e.g. satellite tags) have improved the understanding of life cycles and migratory movements (Renshaw and others, 2023).
Spatial dimension of stock assessments	Improved assessment and management of transboundary and migratory stocks (e.g. FAO 2020; Hidalgo and others, 2024). Increased application of best-practice spatial stock assessment (Goethel and others, 2023; Berger and others, 2024). This implies certain improvements in data collection, data management and data-sharing between jurisdictions (Cope, 2024).
Understanding of life history traits at regional scales	Harmonization of life history research and better understanding of phenotypic and phenological plasticity and spatial variation (Zarco-Perello and others, 2022; Carbonara and others, 2019; Follesa and Carbonara, 2019; Vitale and others, 2019).
Fish populations	Baited remote underwater video systems (BRUVS), hydro-acoustics (Kang and others, 2024) and genomics have improved the understanding of spatial dynamics of global fish communities, biodiversity and habitat associations (Leonetti and others, 2024; Mateos-Molina and others, 2024; Moore and others, 2020; Orozco-Ruiz and others, 2023; Vaux and others, 2021). More accessible, improved data and modelling are increasingly informing the understanding of spatial and temporal trends in fish biomass (e.g. FishGlob initiative; Maureaud and others, 2021; Receveur and others, 2024; Blanchard and Novaglio, 2024; Fredston and others, 2023; Payne 2023; Fuchs and others, 2024).
Threatened species protection	There are area-based conservation measures being applied globally for threatened fish species, especially elasmobranchs. Important shark and ray areas are being identified through IUCN. Since the publication of the first *World Ocean Assessment*, the identification of Important Shark and Ray Areas by IUCN has advanced significantly. These are defined as spatially discrete habitats critical for the survival of sharks and rays, based on science-driven criteria aligned with global conservation frameworks. As of 2025, such Areas have been identified in regions such as the Mediterranean, the western Indian Ocean, the South Atlantic and the South Pacific, with ongoing efforts elsewhere. The Important Shark and Ray Areas process informs spatial planning, MPA design and other conservation measures to protect elasmobranch biodiversity amid environmental change (see https://sharkrayareas.org/about-isras/). New global approaches have been developed to identify essential habitats for elasmobranchs to guide spatial management (Notarbartolo di Sciara, 2021). In Brazil, especially in Rio de Janeiro, pioneering studies have been carried out on shark migration and behaviour to support conservation measures in the South Atlantic (Andrzejaczek and others, 2022; Queiroz and others, 2019, 2021a, 2021b). Globally, action plans are being developed through the Convention on the Conservation of Migratory Species of Wild Animals to support elasmobranch populations (e.g. of the Mediterranean angelshark; see Cancino, 2024). The Convention also provides measures (resolution 14.5) for preventing vessel strikes on marine megafauna (e.g. whale sharks) (Womersley and others, 2024).
Fish behaviour and communication	Developing understanding of intraspecific communication in fish (Looby and others, 2022; Valastro and others, 2024).
Microplastic pollution	There is increasing evidence for the ingestion of microplastics and nanoplastics by fish, but the impacts on biomass and diversity remain unknown (Wootton and others, 2021; Jonathan and others, 2021; Savoca and others, 2021; Tekman and others, 2022).
Deep scattering layers	Deep scattering layers provide an important link between shallow-water and deepwater areas (Peña, 2024).
Understanding of biotic perturbations of the water column	High spatial resolution acoustic and hydrological data (Fernández-Castro and others, 2022).

Source: Prepared by the writing team.

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Subchapter 4E
Marine mammals

Key points

- Major threats to marine mammals include by-catch, chemical pollution, vessel strikes and climate change.
- Anthropogenic noise, plastics and other emerging threats require investigation.
- Quantitative research on the cumulative effects of threats is limited.

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1. Introduction

Marine mammals are top predators and good indicators of environmental change. They face direct, indirect and cumulative anthropogenic threats. Data on their distribution, abundance and trends are incomplete and should be considered top priorities for management and conservation.

Changes in taxonomy since 2018 are related to the definition of subspecies, although some new species have been identified (see https://marinemammalscience.org/science-and-publications/list-marine-mammal-species-subspecies/).

Few threats have been alleviated since the publication of the second *World Ocean Assessment* despite some advancements in threat abatement in a very small number of regional populations. Global climate change poses a significant threat, although its effects are clearest in polar regions (Gulland and others, 2022; Meredith and others, 2019). Although climate change and overfishing are serious ecosystem-level threats, species are also challenged by by-catch, pollution, emerging diseases, vessel strikes and disturbances to animal culture and communities.

2. Environmental changes since the publication of the second *World Ocean Assessment*

Changes in overall status: updates by taxon

Pinnipeds (36 species, including 2 extinct)

Pinnipeds are susceptible to climate change-induced shifts and fisheries interactions (affecting mortality and prey availability). Mid-latitude species are affected by marine heatwaves (Garcia-Aguilar and others, 2018; Backe and others, 2021; Jog and others, 2022). The International Union for Conservation of Nature (IUCN) has updated its information on some pinnipeds since the publication of the second *World Ocean Assessment*: ice-dependent species assessed are in decline. Intensive conservation efforts have improved the status of Mediterranean monk seals (Karamanlidis and others, 2023) and, through national legislation and marine protection frameworks (Monk Seal Alliance, 2024), the status of Hawaiian monk seals (Baker and others, 2025) and Saimaa seals (Auttila and Alakoski, 2025) has improved.

Cetaceans

Mysticetes (15 species)

Changing oceanographic processes in the North-West Atlantic due to climate change have altered the range and foraging behaviour of critically endangered North Atlantic right whales, reducing calving rates and increasing the risks of vessel strikes and fishing gear entanglement (Meyer-Gutbrod and others, 2022). Since 2011, the population has declined to fewer than 400 individuals (Frasier and others, 2024).

Rice's whale (Rosel and Wilcox, 2014; Rosel and others, 2021), which occurs in the north-eastern Gulf of Mexico and numbers approximately 33 individuals, is listed as Endangered under the United States Endangered Species Act and as Critically Endangered on the IUCN Red List of Threatened Species.

Odontocetes (79 species, 1 possibly extinct)

Coastal and estuarine dolphins and porpoises

By-catch continues to be the primary threat (Brownell and others, 2019), with habitat loss and degradation from coastal development and pollution negatively affecting feeding and breeding grounds (Bartalini and others, 2022; Lailson-Brito Jr., and others, 2022). The Critically Endangered Atlantic humpback dolphin (Braulik and others, 2023), found along West Africa, faces threats from artisanal fisheries and rapid coastal development (Genov and others, 2024). To assist with their conservation, the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals adopted resolution 14.10 on the single species action plan for the Atlantic humpback dolphin (*Sousa teuszii*). In 2023, gillnet blocking devices created a sanctuary for vaquitas in Baja California. Rojas-Bracho and others (2024) recommend further development of vaquita-safe fishing gear to allow artisanal fishing. In 2023, the International Whaling Commission (IWC) issued its first-ever extinction alert for the vaquita (IWC, 2023).

Pelagic toothed whales, dolphins and porpoises

Beaked whales (n=24) lack data on population structure and abundance (Feyrer and others, 2024). Threats to these deep-diving species include military sonar, climate change, entanglement, plastic pollution, vessel strikes and oil spills.

Freshwater dolphins

Due to their limited ranges, freshwater dolphins in Asia and South America are endangered by anthropogenic threats (Campbell and others, 2022). In 2023, unprecedented droughts in the Amazon Basin led to extreme water heating and increased dolphin mortality (Grossman, 2024; Fleischmann and others, 2025). Irrawaddy dolphins in the Mekong River are likely extirpated due to population fragmentation as a result of dams, high fishing mortality, vessel strikes, pollutants, genetic outbreeding depression and low recruitment (Krutzen and others, 2018; Dove, 2022).

Sirenians (5 species, including 1 extinct)

Dugong populations are mostly declining outside Australia (Panyawai and Prathep, 2022; Marsh and others, 2025) and are listed as Vulnerable globally (Marsh and Sobtzick, 2019). Three subpopulations have recently been listed by IUCN: New Caledonia (Endangered) (Hamel and others, 2022); Japan (Endangered) (Brownell and others, 2019) and coastal East Africa (Critically Endangered) (Trotzuk and others, 2022). Research on the three manatee species has progressed in the Amazon (Amaral and others, 2023), Caribbean (Galves and others, 2023), Africa (Keith-Diagne and others, 2021; Factheu and others, 2023) and Florida (Brady and others, 2022).



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Other carnivores

Polar bears (1 species)

Trend assessments for all polar bear populations indicate that five are stable, three are increasing and two are declining (Laidre and others, 2022; Polar Bear Specialist Group (PBSG-IUCN), 2023). Improved harvest management and transient improvement in habitat conditions have resulted in improved status for some populations (Dyck and others, 2020; Laidre and others, 2023), while longer ice-free seasons and reductions in ice-seal prey have reduced body condition, productivity and survivorship in others (Dyck and others, 2022; Bromaghin and others, 2015; Atkinson and others, 2022). Given the rate of climate change (Molnár and others, 2020; Stroeve and others, 2024), few polar bear populations are expected to exist beyond 2100.

Mustelids (3 species)

Southern sea otters in western North America have not recovered from hunting, although protection began in 1911 with the North Pacific Fur Seal Convention. The population is estimated at 3,000 (Hatfield and others, 2019). Reintroductions of otters to parts of their historical range are under consideration (Hughes and others, 2019; Rudebusch and others, 2020). There is little information on the marine otter, or chungungo, along the western coast of South America; it is considered Endangered on the IUCN Red List.

Area-based protection

Since 2018, 234 important marine mammal areas for 110 species have been identified by IUCN. Such areas can inform the implementation of area-based management measures, for example the north-west Mediterranean Particularly Sensitive Sea Areas of the International Maritime Organization (see www.marinemammalhabitat.org/immas/immas-searchable-database/).

Changes in overall status

Overall, 26.9% of all marine mammal species (including freshwater species) are under threat (table 1). One third of the 30 species not assessed in the second *World Ocean Assessment* are still classified as Data Deficient. Only two have changed in status (table 2 and figure I): the Mediterranean monk seal, now classified as Vulnerable, and the North Atlantic right whale, now classified as Critically Endangered.

Table 1
Marine mammal species in each category of the International Union for Conservation of Nature Red List of Threatened Species in 2024

Group	Extinct	Critically Endangered	Endangered	Vulnerable	Near Threatened	Least Concern	Data Deficient	Total
Freshwater dolphins		1	4					5
Mysticetes		2	3	1	1	7	1	15
Odontocetes		2	5	6	9	42	9	73
Pinnipeds	2		6	4	1	23		36
Polar bears				1				1
Sea otters			2					2
Sirenians				4				4
Total	**2**	**5**	**20**	**16**	**11**	**72**	**10**	**136**

Source: Prepared by the writing team.

Note: Regional, subspecies or subpopulation assessments are excluded.

Table 2
Changes in the status of marine mammals in the International Union for Conservation of Nature Red List of Threatened Species since the publication of the second *World Ocean Assessment*

Group	New	Uplisted	Unchanged	Downlisted	Data Deficient	Total
Freshwater dolphins	1		4			5
Mysticetes		1	13		1	15
Odontocetes	20		44		9	73
Pinnipeds			35	1		36
Polar bears			1			1
Sea otters			2			2
Sirenians			4			4
Total	**21**	**1**	**103**	**1**	**10**	**136**

Source: Prepared by the writing team.

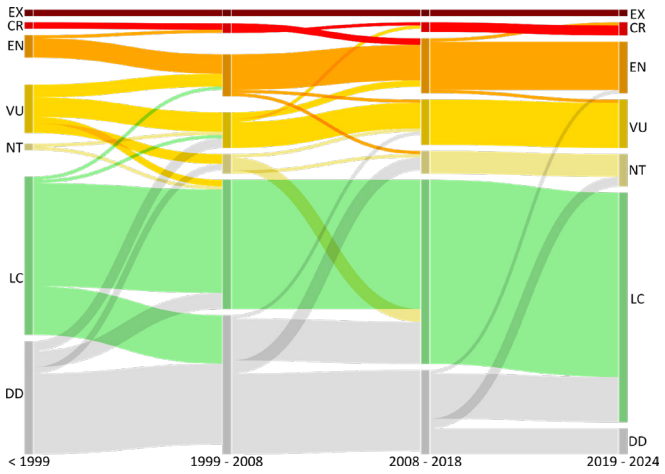
Note: "New" refers to species evaluated after the publication of the second *World Ocean Assessment* or previously Data Deficient; "Uplisted", worsened conservation status; "Downlisted", improved conservation status.

Region-specific changes

Arctic Ocean

Since the publication of the second *World Ocean Assessment*, Arctic marine ecosystems have changed dramatically due to global warming, with temperature increases four times the global average (Meredith and others, 2019; Rantanen and others, 2022). Arctic sea ice has drastically declined in extent and thickness. An ice-free Arctic is predicted for mid-century (Kim and others, 2023), representing virtually total habitat loss for 11 endemic Arctic marine mammal species. Transformed food webs, altered predator-prey relationships, changing distribution and migration patterns, local overharvesting, increasing disease risks and human encroachment are threats (Heide-Jørgensen and others, 2020; Kovacs and others, 2021; Kuletz and others, 2024).

Figure I
Status changes over time



Source: Prepared by the writing team.

Abbreviations: EX, Extinct; CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; DD, Data Deficient.

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Regional downlisting of Mediterranean monk seals, common bottlenose dolphins and striped dolphins and the establishment of the North-Western Mediterranean Particularly Sensitive Sea Areas are examples of positive developments. For example, Greece has designated two new national marine parks, one in the Ionian Sea and one in the Aegean Sea, and is endorsing concrete management actions to ensure high protection and improve species' conservation status. Türkiye has committed to designating new marine protected areas (MPAs) and management actions in the Mediterranean Sea. However, mass strandings of beaked whales and by-catch still raise serious concerns. The Critically Endangered Baltic harbour porpoise (Celemin and others, 2023) and the Endangered Black Sea endemic harbour porpoise are threatened by by-catch in gillnets (International Council for the Exploration of the Sea (ICES), 2024) and in turbot gillnets (Popov and others, 2023).

South Atlantic Ocean and wider Caribbean

Entanglement in fishing gear remains the main threat to coastal marine mammals regionally (Domit and others, 2021; Secchi and others, 2021; da Silva and others, 2023). Although legally protected in most countries, direct take and consumption occur in some countries (Ingram and others, 2022; Nuno and others, 2022).[1] Environmental degradation is considered the leading cause of some population declines (Lailson-Brito Jr and others, 2022; Oliveira-Ferreira and others, 2024). In 2023–2024 the H5N1 avian influenza severely affected South American pinnipeds (Plaza and others, 2024; Uhart and others, 2024).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Since the publication of the second *World Ocean Assessment*, freshwater and oceanic mammals in the Bay of Bengal and its tributaries have been increasingly exposed to human-induced threats, including fisheries, habitat degradation and pollution (Paudel and others, 2020a and 2020b; Campbell and others, 2022). A lack of monitoring and research in some countries limits the availability of information for 23 cetacean species and the dugong.

North Pacific Ocean

Knowledge of cetaceans in the East and South China Seas has increased since the publication of the second *World Ocean Assessment*, with at least 25 cetacean species confirmed in the South China Sea (Liu and others, 2023, 2024a, 2024b; Li and others, 2024). Dugongs may be functionally extinct in China (Lin and others, 2022a). Several populations of Indo-Pacific humpback dolphins have rapidly declined in recent decades, with at least one group facing extirpation (Lin and others, 2022b, 2024a, 2024b). As of 2022, the Yangtze finless porpoise is increasing in numbers after the implementation of a 10-year fishing ban (Hao and others, 2024).

South Pacific Ocean

In Chile, South American sea lions are depredating fish catches, resulting in fishermen illegally killing them (approximately three per boat per month) (Sepulveda and others, 2018). In the South-West Pacific, data on strandings around New Caledonia could be used to determine species distributions and provide samples for genetic, ageing, diet and pollutant analysis (Garrigue and others, 2024).

Southern Ocean

In the Southern Ocean, habitats are shifting polewards, increasing habitat for sub-Antarctic species and reducing habitat for ice-dependent species (Hindell and others, 2020; Melbourne-Thomas, 2020). Antarctic krill distribution has drifted south, with declining sea ice (Kawaguchi and others, 2024) raising concerns because they are the primary prey for blue, fin, humpback, Antarctic and minke whales and crabeater seals. There is also concern about increased vessel traffic associated with ecotourism (Pallin and others, 2022).

Changes in key threatening processes since the publication of the second *World Ocean Assessment*

Fisheries by-catch

Research on by-catch has increased in some countries since the publication of the second *World Ocean Assessment* because of export regulations (e.g. National Oceanic and Atmospheric Administration (NOAA), Office of International Affairs and Commerce, 2023).

[1] Recent initiatives, such as resolution 14.15 of the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals, address the harvest of aquatic wild meat in West Africa.

Good governance and the involvement of local communities are key to addressing artisanal gillnet fisheries threats to small cetaceans globally (Brownell and others, 2019). The Bycatch Risk Assessment toolkit is available for addressing data-poor cases (Hines and others, 2020). In some areas, animals are increasingly using fishing activities as a foraging strategy (e.g. Papageorgiou and others, 2024).

Vessel strikes

A global analysis of the risk of global shipping vessel strikes to four large whale species found that less than 10% of populations had protective measures (Nisi and others, 2024). The International Whaling Commission (IWC) leads global efforts on risk assessment and the identification of mitigation options, advising countries and intergovernmental organizations such as the International Maritime Organization. The Commission hosts a global vessel strike database (Winkler and others, 2020). Reducing the risks of vessel strikes for marine megafauna has been addressed by the Conference of the Parties to the Convention on Migratory Species in its resolution 14.5.

Climate change

Climate change impacts are recognized as a global threat to marine biodiversity, creating both direct and indirect negative effects on marine mammals (Marsh and others, 2022; D'Amen and others, 2024). Since the publication of the second *World Ocean Assessment*, this threat has escalated. Oceans have become warmer, fresher, increasingly stratified and less oxygenated (Intergovernmental Panel on Climate Change (IPCC), 2022). Sea levels have risen, storm activity has intensified and sea ice has declined. These changes affect marine mammals directly, through physical habitat changes, and indirectly, through altered ecosystems. Other climate-related concerns related to marine mammals include increased harmful algal blooms and infectious disease exposure (Kebke and others, 2022; Barratclough and others, 2023) and the impacts of warmer water on sound propagation and exposure to contaminants (Affatati and others, 2022; Borgå and others, 2022).

Contaminants

Legacy compounds identified in the second *World Ocean Assessment* have declined in many species but continue to accumulate in animal tissues in some regions despite being banned under the Stockholm Convention[2] on Persistent Organic Pollutants (2004). Novel contaminants, especially perfluoralkyl compounds and microplastics (Schaap and others, 2023), now add to threats.

Diseases

Harmful algal blooms

Since the publication of the second *World Ocean Assessment*, climate change has increased the spatiotemporal distribution of harmful algal blooms globally (Hallegraeff and others, 2021), which can cause marine mammal death and disease. Saxitoxin, a neurotoxin found in shellfish contaminated by harmful algal blooms, has recently been detected north of the Bering Strait for the first time (Lefebvre and others, 2022). Harmful algal blooms have been responsible for the deaths of sirenians, dolphins and baleen whales (Haussermann and others, 2017; Starr and others, 2017; Broadwater and others, 2018).

Infectious diseases

Multiple viral epizootics have caused severe die-offs of marine mammals since the publication of the second *World Ocean Assessment*. Morbilliviruses have killed thousands of cetaceans and pinnipeds (Duignan and others, 2014; Van Bressem and others, 2014; Groch and others, 2018). Die-offs of pinnipeds in South America in 2022 and 2023 were caused by the avian influenza virus H5N1 (Ulloa and others, 2023; Uhart and others, 2024).

The spread of terrestrial pathogens to marine mammals has been facilitated by coastal development and increases in coastal run-off. Toxoplasmosis causes mortality globally, killing critically endangered Māui dolphins in New Zealand, monk seals in Hawaii and sea otters in the United States of America (Barbieri and others, 2016; Miller and others, 2018).

Offshore wind energy production

Worldwide production of offshore wind energy has expanded rapidly. Both exploration and implementation pose risks to marine mammals (Macrander and others, 2022). Passive acoustic monitoring can be used to define critical habitats and reduce the risk of vessel strikes, as studies in New England, for example, have shown (Van Parijs and others, 2023).

[2] See www.sciencedirect.com/topics/earth-and-planetary-sciences/stockholm-convention.

Tourism

Wildlife tourism is growing in scale and revenue (O'Connor and others, 2009). Recent research enables the quantification of disturbance of unmanaged tourism at population levels (Bejder and others, 2022). Possible physiological and behavioural consequences can lead to decreased health and survival (Booth and others, 2022). The Secretariat of the Convention on Migratory Species has developed a publication, *International Guidelines for Sustainable Marine Wildlife Interactions: Boat-Based and In-Water Activities* (CMS Technical Series Publication No. 49).

3. Key remaining knowledge and capacity gaps

Knowledge and capacity-building gaps	Steps taken to address gaps since the publication of the second *World Ocean Assessment*
Global distribution, abundance and population structure	Advances in satellite imagery and artificial intelligence (Cubaynes and others, 2023)
	Regional and international large-scale surveys (e.g. Gilles and others, 2023; Panigada and others, 2023)
	Marine acoustics (Ferguson and others, 2023; Cominelli and others, 2024)
	Advances in genetics (McGowen and others, 2024; Morin and others, 2024)
Species-specific distribution modelling	Advances in habitat use modelling (Bedrinana-Romano and others, 2022; Cañadas and others, 2023; Fiedler and others, 2023; Frantz and others, 2024)
Spatiotemporal identification of climatic refugia for marine mammals	Creation of climate refugia (Gulland and others, 2022; Garcia-Reyes and others, 2023; Zelli and others, 2025)
Plastics and microplastics	Research on the effects of microplastics on marine mammals (Zantis and others, 2021)

Source: Prepared by the writing team.



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Subchapter 4F
Marine reptiles

Key points

- Updates were identified across various marine reptile taxa, with some species maintaining their global conservation status, while others (e.g. green turtles) have new classifications ranging from Least Concern to Endangered.
- The present *Assessment* includes saltwater crocodiles, classified as Least Concern due to stable global populations resulting from effective regional management in the species' range.
- Ongoing threats, such as incidental fisheries bycatch, remain significant, and additional challenges, such as habitat degradation, marine pollution and climate change, require more comprehensive conservation strategies.
- Gaps remain in long-term monitoring and the gathering of population trend data for marine reptiles, particularly sea snakes and marine iguanas.

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1. Introduction

The present subchapter contains an update on the global and regional statuses of the four major marine reptile groups: marine turtles (7 species), sea snakes (71 species), marine iguanas (1 species) and saltwater crocodiles (1 species). These species range from widely distributed (e.g. sea snakes) to highly localized (e.g. marine iguanas in the Galapagos Islands) and inhabit environments ranging from the open ocean (e.g. marine turtles) to coastal and estuarine habitats (e.g. saltwater crocodiles). The chapters on marine reptiles in the first *World Ocean Assessment* (Wallace and others, 2016) and the second *World Ocean Assessment* (Schuyler and others, 2021) contained an outline of the baselines and trends for these groups (except saltwater crocodiles) up to 2018. The second *World Ocean Assessment* highlighted variable changes in marine turtle populations, showing some recovering (e.g. loggerhead sea turtle), others stable (green sea turtle) and some declining (Kemp's ridley sea turtle). It highlighted the reclassification of two Critically Endangered sea snake species (short-nosed and leaf-scaled sea snakes) to Data Deficient, added three new species (mosaic, Shark Bay and rough-scaled) assessed as Data Deficient, and highlighted subspecies reclassification in marine iguana without altering their overall status (MacLeod and others, 2020a; Miralles and others, 2017). This will be the first *Assessment* to include saltwater crocodiles.

2. Overall status of marine reptiles

Marine turtles

There have been no updates to the global status of any of the seven marine turtle species since the publication of the second *World Ocean Assessment*, but green turtle (*Chelonia mydas*) subpopulations were newly assessed. Four subpopulations were classified as Least Concern (south-west Indian Ocean), Near Threatened (Mediterranean), Vulnerable (East Pacific) and Endangered (central South Pacific). Loggerhead (*Caretta caretta*), leatherback (*Dermochelys coriacea*) and olive ridley (*Lepidochelys olivacea*) turtles remain Vulnerable (Casale and Tucker, 2017; Abreu-Grobois and Plotkin, 2008). Hawksbill (*Eretmochelys imbricata*) and Kemp's ridley (*Lepidochelys kempii*) turtles are still Critically Endangered (Mortimer and Donnelly, 2008; Wibbels and Bevan, 2019), and flatback turtles (*Natator depressus*) remain Data Deficient, with no updates since 1996. The Marine Turtle Specialist Group has revised regional management units to define biologically meaningful populations (Wallace and others, 2023) and has updated conservation priorities for all species and regional management units (Wallace and others, 2025).

Sea snakes

Since the publication of the second *World Ocean Assessment*, the status has not been updated, but a newly described subspecies, the yellow sea snake (*Hydrophis platurus xanthos*), has been assessed as Endangered under the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Bessesen and others, 2024). Among the 71 species and one subspecies currently recognized, one species (*Aipysurus fuscus*) and one subspecies (*Hydrophis platurus xanthos*) are Endangered, three are Vulnerable (*Hydrophis semperi*, *Laticauda crockeri* and *Laticauda schistorhynchus*), four are Near Threatened (*Hydrophis pacificus*, *Laticauda semifasciata*, *Laticauda frontalis* and *Laticauda guineai*) and 35 are Least Concern, while the remaining 27 species are either Data Deficient or have yet to be assessed. Marine surveys in north-western Australia have in deep waters documented populations of *Aipysurus apraefrontalis*, which had been previously presumed to be locally extinct as a result of surveys done in shallower waters (Somaweera and others, 2021).



Sina Ritter



Nuria Bufort Costa

Marine iguanas

The conservation status of the marine iguana (*Amblyrhynchus cristatus*) was updated in 2019, with the global status remaining Vulnerable (MacLeod and others, 2020a). The Fernandina Island subspecies was assessed as Vulnerable (MacLeod and others, 2020b); six subspecies from Santiago, Española, San Cristóbal, Wolf, Marchena and Santa Cruz islands as Endangered (MacLeod and Steinfartz, 2016); and the four remaining subspecies from Isla Santa Fé, Pinta, Genovesa and Punta Pitt are Critically Endangered (MacLeod and others, 2020a).

Saltwater crocodiles

The saltwater crocodile (*Crocodylus porosus*) was last assessed in 2019 in the IUCN Red List, retaining its Least Concern global status with a stable global population exceeding 400,000 non-hatchlings (Webb and others, 2021). This species breeds mainly in rivers and swamps, undertaking long sea journeys associated with foraging and mate-searching (Manolis, 2005). The species is widely distributed across South and South-East Asia, Australia and Melanesia; however, its population is now extinct in the wild in Seychelles, and possibly extinct in Cambodia, Thailand and Viet Nam (Webb and others, 2018).

3. Regional trends

Regional trends in nesting and foraging marine turtle populations have shown positive developments since the publication of the second *World Ocean Assessment*. A review by the Marine Turtle Specialist Group assessed population status between the years 2011 and 2024, scoring risk factors and threats within regional management units (Wallace and others, 2025). While 74% of regional management units had improved since 2011, with notable increases in hawksbill and green turtle populations in the Chagos Archipelago (Mortimer and others, 2020) and the Red Sea (Shimada and others, 2021), 26% of regional management units worsened in both risk and threat categories (see table 1). Fisheries by-catch remains the highest-ranked threat (Wallace and others, 2025). A meta-analysis of 61 long-term nesting surveys showed increasing or stable trends for most populations, while highlighting declines in leatherback and loggerhead populations (Hays and others, 2024).

For sea snakes, decreasing population trends have been identified in locations where data are available (including the Gulf of Thailand, India and New Caledonia), while several other locations lacked sufficient data to define trends (see table 2). Overall population trend information is lacking for marine iguanas, with some subpopulations undergoing extreme fluctuations (MacLeod and others, 2020a). Indicative subspecies trends were identified in 2019 with either decreasing or unknown trends in population abundance (see table 2). Saltwater crocodile populations have stabilized since historical exploitation, with the species' global status improving from Endangered status in 1982 to Least Concern in 2019 (Webb and others, 2021). This is largely due to their effective regional management in Australia, Papua New Guinea and Indonesia. Regional assessments highlight a trend towards increase in Solomon Islands, the Philippines and in the states of Sarawak and Sabah in Malaysia due to effective protection measures, but declines in Myanmar (table 2).

Table 1
Summary of marine turtle regional population trends (2018–2023) by regional management unit, with references

Region	Green	Loggerhead	Hawksbill	Olive ridley	Kemp's ridley	Leatherback
North Atlantic Ocean, Caribbean Sea and Mediterranean Sea	*Increasing:* North-West Atlantic Ocean, Caribbean [1] Mediterranean Sea [2] *Decreasing:* Costa Rica [3]	*Stable:* North-West Atlantic Ocean [4]	*Increasing:* Gulf of Mexico [1] *Stable:* Caribbean, Saint Croix [5] *Decreasing:* Caribbean, Saint Croix [5]	*No updates*	*Stable:* Gulf of Mexico [6]	*Decreasing:* North-West Atlantic Ocean, Caribbean [7]
South Atlantic Ocean	*Stable:* Sao Tome and Principe [8]	*No updates*	*No updates*	*Increasing:* West Africa [7] *Stable:* French Guiana [9]	*Stable:* Gulf of Mexico [6]	*Increasing:* Brazil [10] *Decreasing:* Brazil [7]
Indian Ocean, Red Sea, Arabian Sea and Persian Gulf	*Increasing:* Saudi Arabia [11] *Stable:* Egypt, Islamic Republic of Iran, Kuwait, Pakistan [11] South-west Indian Ocean [12] Maldives [13] North-west Indian Ocean [11] *Decreasing:* Bangladesh, Maldives [11]	*Increasing:* South-West Indian Ocean [12] *Stable:* South-West Indian Ocean [12] Maldives [13] *Decreasing:* Oman [11]	*Increasing:* Maldives, Saudi Arabia [11] Bangladesh [11] *Stable:* North-West Indian Ocean [11]	*Increasing:* Bangladesh [11] *Stable:* North-East Indian Ocean, West Indian Ocean [11]	*Outside range*	*Stable:* India [11] South-West Indian Ocean [12] *Decreasing:* Bangladesh [11]
North Pacific Ocean	*Increasing:* North-central Pacific Ocean regional management unit [14] North Mariana Islands [15] *No trend:* Guam [16]	*No updates*	*No updates*	*Stable:* Costa Rica, Mexico [7]	*Outside range*	*Decreasing:* Costa Rica [17]
South Pacific Ocean	*Increasing:* French Polynesia [18] New Caledonia [19] *Stable:* Australia [7] *Decreasing:* Raine Island (Australia) [20]	*No updates*	*Decreasing:* Great Barrier Reef (Australia) [21]	*No updates*	*Outside range*	*No updates*

Source: Prepared by the writing team.
References: [1] López-Castro and others, 2022; [2] Casale and others, 2018; [3] Restrepo and others, 2023; [4] Ceriani and others, 2019; [5] Gulick and others, 2022; [6] Arendt and others, 2023; [7] Hays and others, 2024; [8] Ferreira-Airaud and others, 2022; [9] Nalovic and others, 2018; [10] Colman and others, 2019; [11] Phillott and Rees, 2021; [12] Dalleau and others, 2020; [13] Hudgins and others, 2023; [14] Chaloupka and Pilcher, 2019; [15] Summers and others, 2018; [16] Valdivia and others, 2019; [17] Eastern Pacific Leatherback Conservation (The Laúd OPO Network), 2020; [18] Touron and others, 2018; [19] Fretey and others, 2023; [20] Dunstan and others, 2020; [21] Bell and others, 2020.
Note: Metrics include nesting counts and individual observations across five major regions.

Table 2
Summary of regional population trends for sea snakes, marine iguanas and saltwater crocodiles (2018–2023), categorized as increasing, stable, decreasing or unknown, with references

Region	Sea snake	Marine iguana	Saltwater crocodile
Indian Ocean, Red Sea, Arabian Sea and Persian Gulf	*Decreasing:* Gulf of Thailand [1] India [2] *Unknown trend:* Western Australia [3] Persian Gulf [4]	*Outside range*	*Increasing:* Western Australia [5] India [6] Peninsular Malaysia [7] *Decreasing:* Myanmar [8],[9] *Unknown trend:* Bangladesh [10] Indonesia [11] Sri Lanka [12]
North Pacific Ocean	*Unknown trend:* Costa Rica [13]	*Outside range*	*Increasing:* Malaysian Borneo, Brunei [14] Philippines [23] *Stable:* Palau [14] Singapore [25]
South Pacific Ocean	*Decreasing:* New Caledonia [15] Eastern Australia [16]	*Decreasing:* Isla Punta Pitt, Genovesa, Pinta and Santa Fé subspecies [17] *Unknown trend:* Fernandina Island, Santa Cruz, Marchena, Wolf, San Cristóbal, Española, Santiago subspecies [18]	*Increasing:* Northern Australia [19] Papua New Guinea [20] Solomon Islands [21] Timor-Leste [22] Vanuatu [14] *Unknown trend:* Indonesia [24]

Source: Prepared by the writing team.

References: [1] Cao and others, 2014; [2] Rao and others, 2021; [3] Speed and others, 2022; [4] Yaghmour and others, 2022; [5] Parke, 2015, and Wildlife Management International, 2018; [6] Kar, 2024; [7] Kwan, 2017; [8] Platt and others, 2015; [9] Than and others, 2024; [10] Somaweera, personal communication; [11] Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), 1994; [12] Amarasinghe and others, 2015; [13] Bessesen and others, 2022; [14] Webb and others, 2021; [15] Shine and others, 2021; [16] Edgar and others, 2020; [17] MacLeod and others, 2020a; [18] MacLeod and others, 2020b; [19] Saalfeld and others, 2016; [20] Solmu and others, 2014; [21] Van der Ploeg and others, 2019; [22] Brackhane and others, 2019; [23] CITES, 2022; [24] Saragih and others, 2020; [25] Figueroa and others, 2023.

4. Changes in key threats

Key threats to marine reptiles, such as by-catch and targeted harvest, remain significant, with emerging threats such as light pollution, habitat modification and climate change also becoming increasingly impactful (Senko and others, 2022; Fukuda and others, 2022).

Targeted harvest and by-catch

Fisheries by-catch remains the greatest threat to marine turtles, with large numbers caught annually across multiple gear types (Lewison and others, 2014; Wallace and others, 2013). Data gaps in regions such as West Africa (de la Hoz Schilling and others, 2023; Segniagbeto and others, 2017), the Eastern Pacific (Griffiths and others, 2024), continental Europe (Marco and others, 2020; Casale and others, 2018) and North America (Savoca and others, 2020) limit effective management. The Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals has adopted several region- and species-specific action plans for marine turtles for West Africa, South-East Asia and the western Pacific. Sea snake populations in the Gulf of Thailand and India have declined due to increased fishing and unregulated fishing practices (Rao and others, 2021). Including sea snakes and marine turtles in the Marine Stewardship Council certification process could help to limit fisheries impacts on these populations (Good and others, 2024; see also

subsect. 5A, subchap. 1A). Saltwater crocodiles still face legal and illegal take (Webb and others, 2021), and while egg harvesting has minimal impact, adult harvesting (Fukuda and others, 2020) and drowning as by-catch in fishing nets remain concerning. Legal hunting for meat poses a comparatively smaller and localized threat to the species (Brackhane and others, 2019). At the fourteenth Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals (2024), the Action Plan on Aquatic Wild Meat Harvests in West Africa was adopted, which addressed species including reptiles and was aimed at bringing policy and scientific attention to these regional harvests and promoting sustainable management.

Habitat degradation, marine pollution and coastal modification

Marine debris, particularly plastics, affects marine turtle reproductive ecology, although the population-level impacts remain unclear (Duncan and others, 2021; Fuentes and others, 2023). Habitat loss due to oil and gas developments (Nelms and others, 2016), renewable-energy technologies (Maxwell and others, 2022) and seabed mining (Williams and others, 2022) continues to threaten marine turtles. Coastal artificial lighting disorients marine turtle hatchlings and deters nesting females (Leader and others, 2024); however, species-specific guidelines to mitigate these impacts have been developed (e.g. the International Light Pollution Guidelines for Migratory Species, prepared by the Secretariat of the Convention on Migratory Species). Oil spills have caused mass mortalities of sea snakes in the Gulf of Oman (Yaghmour and others, 2022). Marine iguanas face threats from habitat degradation (Pizzitutti and others, 2017; Walsh and Mena, 2016), oil spills (Wikelski and others, 2002), alien species (Wikelski and Nelson, 2004) and tourism-induced stress (French and others, 2010; see also subsect. 5A, chap. 4). Plastic pollution has emerged as a serious threat to marine iguana populations through ingestion and entanglement (Muñoz-Pérez and others, 2023). Saltwater crocodile nesting habitats are increasingly threatened by urban encroachment, sand mining, aquaculture and coastal agriculture (Fukuda and others, 2022).

Climate change associated impacts

Climate change threatens marine turtles by reducing nesting habitat and reproductive success, with warmer nest temperatures leading to more female hatchlings than males (Patrício and others, 2021). Impacts from altered reproductive periodicity, reduced foraging quality, and range shifts are also anticipated (Fuentes and others, 2023). However, nesting populations farther from the equator show greater resilience to temperature increases (Laloë and Hays, 2023). Sea-level rise poses a major threat to saltwater crocodiles, particularly coastal mound-nesting populations (Fukuda and others, 2022). Marine iguanas are vulnerable to climate fluctuations, especially during strong El Niño years, when increased water temperatures reduce the abundance of marine algae, their primary food source (Dueñas and others, 2021). The frequency of climate fluctuation events is predicted to increase due to climate change, further threatening marine iguana survival and reproductive success (Cai and others, 2014; MacLeod and others, 2020a).

5. Key knowledge and capacity gaps

Marine turtles

Data gaps persist for loggerhead, green, leatherback, hawksbill, and olive ridley turtles across various regional management units (Wallace and others, 2025). Variability in subpopulation status and threats require ongoing species and regional assessments. Stock assessment models are needed to understand the levels of mortality that the population can sustain without declines (Putman and others, 2020). Greater understanding is needed of the effects of climate change on migratory patterns, cumulative impacts and the effectiveness of conservation strategies.[1] Standardized methods for plastic impact studies and for measuring the sociocultural aspects of traditional turtle harvesting are also necessary (Poti and others, 2021). Further studies are needed to understand the benefits of by-catch management (Arlidge and others, 2020; Gilman and others, 2023), fishery closures, nesting beach management (e.g. nest shading) and hatchery practices (Phillott and others, 2021) for population recovery.

[1] The Conference of the Parties to the Convention on Migratory Species has adopted resolution 12.21 (Rev.COP14) on climate change and migratory species, including a list of priority actions to address this issue.

Sea snakes

As most sea snake populations lack long-term monitoring, data on trends and distribution, as well as threats such as by-catch, habitat degradation and climate change, are scarce (Udyawer and others, 2018). Rising ocean temperatures will affect sea snake physiology, reducing diving capacity and increasing mortality during incidental by-catch in trawl nets (Udyawer and others, 2016). Research shows shifts in sea snake assemblages due to unregulated fishing (Rao and others, 2021), but there are gaps in the tracking of population trends. A better understanding of national and international regulations on the trade in sea snakes is needed for assessing actual global harvesting levels (Báez and others, 2024).

Marine iguanas

The lack of long-term monitoring and the collection of census data for marine iguanas hinders the evaluation of population trends and threats (Alava and others, 2023). Knowledge is still lacking on plastic pollution impacts on population health (Jones and others, 2021; Muñoz-Pérez and others, 2023). The Galapagos Islands experienced El Niño events in 2015/16 and 2023/24 (National Oceanic and Atmospheric Administration (NOAA), 2022), climatic phenomena known to significantly impact iguana population health by increasing metabolic stress and reducing food availability (Varela-Jaramillo and others, 2023). While no census data exists for the 2015/16 event, drone-based surveys established before the 2023/24 El Niño event will allow for the future assessment of population trends in response to El Niño events (Varela-Jaramillo and others, 2023).

Saltwater crocodiles

Assessments of wild saltwater crocodile populations are lacking across much of their range, with basic population estimates absent in countries such as Brunei Darussalam, Cambodia, Timor-Leste and Indonesia. A growing number of human-crocodile conflicts (Baker and others, 2024) highlights the need for locally tailored management programmes (Webb and others, 2021). The close link between the production and trade of crocodilian products in South-East Asia underscores the need for coordinated management, conservation and regulatory efforts. Captive breeding programmes exist, but lack survival assessments, which would require reviews of restocking practices and release-site protocols (Corey and others, 2018).

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Subchapter 4G
Seabirds

Key points

- Seabirds remain one of the most threatened species groups at the global level, with 31% considered threatened with extinction.
- Invasive alien species and incidental fisheries bycatch remain among the major threats to seabird species, and the number of species affected by these threats has increased since the publication of the second *World Ocean Assessment*.
- Seabirds are increasingly facing the impacts of emerging processes, such as outbreaks of highly pathogenic avian influenza (HPAI), the development of offshore wind farms and the increase in plastic and light pollution.
- Research priorities include understanding the population trends and at-sea distribution of burrow nesters (such as storm petrels and other small petrels) and understanding the population-level effects of cumulative threats.

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1. Introduction and context

Seabirds, which are bird species that depend on marine ecosystems for at least part of the year, are either top predators or skilled scavengers that play important roles in marine food webs (Brooke, 2004). They are found in all oceans, from coastal waters to the high seas. Although most seabirds are restricted to surface waters, they interact with other marine species living at different depth-layers, from the epipelagic to the mesopelagic and bathypelagic zones (e.g. by preying upon marine animals such as fish, squid or crustaceans, or by foraging in association with marine mammals). There are currently 366 extant seabird species recognized across nine different orders (see table 1). Many species are migratory and travel great distances from their breeding colonies to their foraging grounds. For this reason, seabirds are recognized as key biological vectors of nutrients, which they collect from large oceanic areas and concentrate at their colonies (Graham and others, 2018; Benkwitt and others, 2022).

Seabirds are relatively well-studied compared with other marine species, allowing for the compilation of extensive information on their conservation status, population trends and main threats, with global assessments led by BirdLife International (Croxall and others, 2012; Dias and others, 2019). These studies have revealed that seabirds are severely impacted by human activities worldwide, with 31% of species threatened with extinction and 57% with declining population trends (see table 1).

Table 1

Number of seabird species in each International Union for Conservation of Nature Red List of Threatened Species category in 2024, and percentage of species with declining population trends

Seabird order	EX	CR	EN	VU	NT	LC	DD	Percentage of species classified as threatened[a] (CR+EN+VU)	Percentage of species in decline[b]	All species
Procellariiformes (tubenoses)	2	17	20	29	20	57	3	46	59	148 (130)
Charadriiformes (gulls and auks)	1	1	4	11	10	95		13	48	122 (103)
Suliformes (gannets and boobies)	1	1	5	9	2	28		33	61	46 (36)
Anseriformes (sea ducks)	1			4	3	14		19	67	22 (18)
Sphenisciformes (penguins)			5	4	2	7		50	71	18 (17)
Gaviiformes (loons)					1	4		0	60	5 (5)
Podicipediformes (grebes)				1		3		25	100	4 (2)
Phaethontiformes (tropicbirds)						3		0	100	3 (3)
Pelecaniformes (pelicans)					1	2		0	0	3 (2)
All species	**5**	**19**	**34**	**58**	**39**	**213**	**3**	**31**	**57**	**371 (316)**

Source: Prepared by the writing team.

Abbreviations: EX, Extinct; CR, Critically Endangered; EN, Endangered; LC, Least Concern; NT, Near Threatened; VU, Vulnerable; DD, Data Deficient.

Note: Threatened species are those classified as CR, EN or VU. In parenthesis ("All species" column) is number of species with known population trends.

[a] The calculation of the percentage of threatened species excluded EX and DD species.
[b] Only species with known population trends were considered.

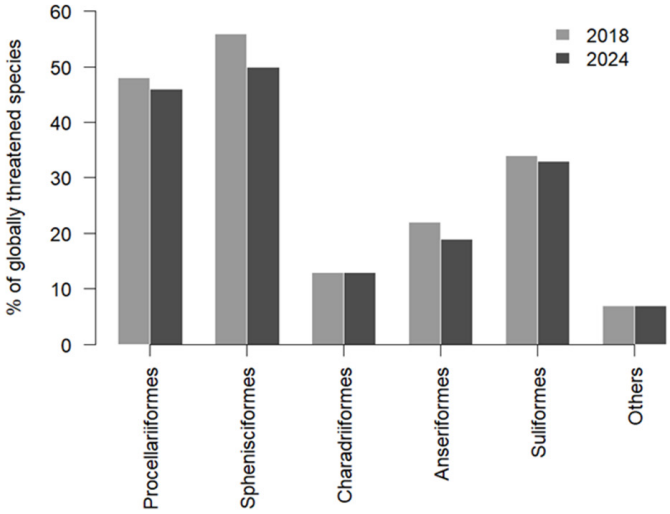
2. Changes in the status of seabirds since the second *World Ocean Assessment*

An overview of the conservation status of seabird species in 2024 is provided in table 1 (BirdLife International, 2024). The procellariiformes (tubenoses such as albatrosses and petrels) are the largest group of seabirds and have the highest number of globally threatened (Critically Endangered, Endangered and Vulnerable) and Near Threatened species of any vertebrate group, according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Sphenisciformes, namely penguins, stand out as the group with the highest percentage of threatened species (50%) and the highest percentage of declining population trends (excluding the tropical birds and grebes, which have few species) (table 1).

The overall conservation status of seabirds (measured as the percentage of species classified as threatened by IUCN) has remained relatively stable since the publication of the second *World Ocean Assessment* (30.8% and 30.6%, respectively). However, an improving trend is reflected in the slight decrease in the percentage of threatened species in some groups (figure I) and in the decrease in the number of "uplisted" species between 2018 and 2024 (table 2). Six species were uplisted (i.e. their conservation status deteriorated) between 2021 and 2025 (an average of 1 species per year), while 28 species were uplisted between 2010 and 2018 (an average of 3.5 per year). However, these numbers should be interpreted with caution, as changes can be due to improved knowledge (e.g. taxonomy changes or new colonies found) rather than a genuine change in status. In fact, the percentage of species with declining population trends has increased since the last assessment, from 47% (Dias and others, 2019) to 57% (table 1). It should also be noted that the most recent assessment of the IUCN Red List status of most seabird species was carried out before the recent outbreaks of HPAI, which caused the mortality of significant proportions of the populations in some seabird colonies (e.g. Falchieri and others, 2022; Leguia and others, 2023).

Figure I

Percentage of species categorized as globally threatened (i.e. Critically Endangered, Endangered or Vulnerable, following International Union for Conservation of Nature classification), by seabird order, in 2018 (reported in the second *Assessment*) and in 2024 (the third *Assessment*)



Source: Prepared by the writing team.

Note: "Others" include orders with five species or fewer (Gaviiformes, Phaethontiformes, Pelecaniformes and Podicipediformes; see table 1).

3. Changes in pressures since the second *World Ocean Assessment*

The main threats affecting seabird populations are well-known and can mostly be attributed to human activities in both marine and terrestrial habitats (Dias and others, 2019; see also sect. 4, chap. 5). At sea, the fisheries sector has been the main cause of population declines (figure II), in particular through the incidental capture of seabirds in fishing gear (incidental by-catch) and prey depletion due to overfishing (Votier and others, 2023; Phillips and others, 2024; see also subsect. 5A), followed by pollution. In colonies, the introduction of invasive species (see sect. 4, chap. 6) is causing severe declines, particularly for species that breed on isolated islands (such as predation by cats and rodents, habitat degradation by introduced herbivores; see, e.g., Spatz and others, 2017). Another ongoing threat in colonies is the direct harvest of eggs, chicks or adult birds for human consumption (Dias and others, 2019). The number of threatened species affected by these pressures has increased since the publication of the first *World Ocean Assessment* (figure II).

Table 2
Summary of changes in the International Union for Conservation of Nature Red List of Threatened Species status of seabirds between 2018 and 2024

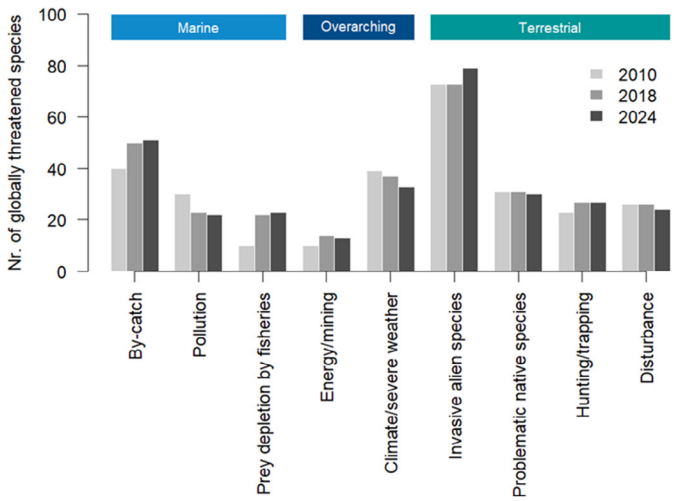
Seabird order	Uplisted[a]	Unchanged	Downlisted	Data Deficient	Total
Procellariiformes (tubenoses)	3 (11)	130	5	2	140
Charadriiformes (gulls and auks)	2 (8)	115	3		120
Suliformes (gannets and boobies)	(2)	43	2		45
Anseriformes (sea ducks)	1 (5)	20			21
Sphenisciformes (penguins)	(1)	15	3		18
Gaviiformes (loons)		5			5
Podicipediformes (grebes)	(1)	4			4
Phaethontiformes (tropicbirds)		3			3
Pelecaniformes (pelicans)		3			3
Total	**6 (28)**	**338**	**13**	**2**	**359**

Source: Prepared by the writing team.

Note: Includes only the 359 extant seabird species analysed in Dias and others (2019). "Uplisted" refers to a deterioration in conservation status in 2024 compared with 2018, while "downlisted" refers to an improvement in conservation status.0

[a] In parentheses, the number of uplisted species reported in the second *World Ocean Assessment*.

Figure II
Number of globally threatened seabird species negatively affected by marine, terrestrial and overarching processes in 2010, 2018 and 2024



Source: Prepared by the writing team.

In addition, seabirds increasingly face emerging threats, such as the development of offshore wind farms (sect. 4, chaps. 5 and 6), the increase in plastic and light pollution (ibid.) and the spread of highly lethal diseases such as avian influenza (Phillips and others, 2023). As numerous studies have reported the negative impacts of these emerging threats since the publication of the second *World Ocean Assessment*, the following paragraphs focus on them, as well as on information updated since the publication of the second *World Ocean Assessment* on fisheries by-catch and prey depletion.

Pollution, with a special focus on plastics and light

Seabirds continue to be affected by pollution from marine and terrestrial sources (Lavers and others, 2014; Provencher and others, 2019; Clark and others, 2023). While reductions in oil spills affecting seabird species have been noted (Dias and others, 2019), plastic pollution remains a threat to many seabirds through ingestion and toxic chemical release (Provencher and others, 2018; Hamilton and others, 2023; Navarro and others, 2023; Vanstreels and others, 2023). Seabirds foraging in the Mediterranean and Black Seas are at particularly high risk of exposure to plastic pollution, although data is still lacking to evaluate the risk of seabirds encountering and ingesting plastic in other regions with high levels of plastic pollution, such as the coastal waters around East and South-East Asia and the South Pacific and North Atlantic gyres (Clark and others, 2023).

Sub-lethal responses of seabirds to plastics have begun to be explored (e.g. Charlton-Howard and others, 2023; Kreitsberg and others, 2023; Serafini and others, 2024). However, the consequences of plastic ingestion and associated chemical contamination at the population level are still poorly understood.

Light pollution poses a significant risk to some species near colonies and marine structures as a result of disorientation, collision or grounding, which can result in injury or mortality (Rodríguez, 2023). In contrast, the effects of light pollution at sea (e.g. from ships, offshore infrastructure or light-attracting fisheries) are poorly

documented. Mitigating these effects requires the large-scale reduction and management of light pollution sources.

Offshore wind farm development

The demand for renewable sources of energy is leading to an exponential increase in the development of offshore wind farms. Seabirds are particularly vulnerable to these and can be affected directly, by collision with turbines, and indirectly, through habitat loss due to displacement effects (e.g. Dierschke and others, 2016). Of particular concern is the potential cumulative impact of multiple facilities, especially for migratory species that travel hundreds or thousands of kilometres per year. Recent studies have assessed this concern (e.g. Goodale and others, 2019; Garthe and others, 2023), although the vast majority are limited to relatively small regions often located in northern countries (Europe and North America) and are focused on breeding species. Potential impacts of offshore wind farms on migrating seabirds (by means of the barrier effect, i.e. when wind farms cause an obstacle to the regular movement of birds) are still poorly understood.

Highly pathogenic avian influenza

HPAI has emerged as a new threat with serious implication for seabirds on a global scale. In contrast to low pathogenicity avian influenza, which circulates asymptomatically in waterbirds (Gass and others, 2023), HPAI causes severe illness and high mortality. Prior to 2017, positive HPAI cases in seabirds were localized and sporadic, and the overall prevalence of active infection was considered very low (Lang and others, 2016). However, in 2017, the Goose/Guangdong (Gs/GD) clade 2.3.4.4b H5N8 avian influenza virus caused mass die-offs of coastal seabird species, such as terns and African penguins (*Spheniscus demersus*) along the southern South African coasts (Peyrot and others, 2022), and was confirmed in 15 seabird species by 2018. It then reappeared in 2021 (Roberts and others, 2023), when the clade 2.3.4.4b H5N1 avian influenza virus caused mass die-offs of great skuas (*Stercorarius skua*) in Scotland (Banyard and others, 2022), and was dwarfed by the re-emergence of H5N1 in early 2022, which spread throughout the North Atlantic, affecting at least 10 seabird species in Great Britain alone (Caliendo and others, 2022; Falchieri and others, 2022). In late 2022, H5N1 spread to South America and caused unprecedented mass die-offs of seabirds in Peru (Leguia and others, 2023). In early 2023, HPAI spread to Chile and Uruguay and, worryingly, jumped to marine mammals, causing parallel mass die-offs (Ulloa and others, 2023). In late 2023, positive samples were detected in several bird species in the Antarctic region (Banyard and others, 2024).

In addition, the impact of HPAI appears to vary among species, with some being particularly affected (i.e. experiencing higher levels of mortality or higher incidence at the colonies when compared with other species), such as the northern gannet (*Morus bassanus*), the common guillemot (*Uria aalge*) and the great skua in the North Atlantic, as well as the Peruvian pelican (*Pelecanus thagus*) and the Peruvian booby (*Sula variegata*) in the southern Pacific (Banyard and others, 2022; Gamarra-Toledo and others, 2023; Lane and others, 2023; McPhail and others, 2024).

Fisheries by-catch and overfishing

Severe impacts of fishing activities on seabirds (as a result of birds getting caught as by-catch or as a result of direct competition for food resources) have been highlighted since the publication of the first *World Ocean Assessment*. Following the publication of the second *World Ocean Assessment*, new studies have provided further detail on the magnitude of these impacts.

A review of the impact of fisheries on seabirds by Votier and others (2023) concluded that, although the problem of seabird by-catch was recognized in the late 1980s (Brothers and others, 1999), it continues to have significant impacts. Suggested avenues to address this threat include improved compliance monitoring of by-catch mitigation measures (including on small-scale fleets and with a special focus on less-known, poorly studied species and regions). Votier and others (2023) also highlighted the urgent need to understand the combined effects of fisheries and other threats, in particular emerging issues such as climate change and offshore wind farms. Ramírez and others (2024) provided, for the first time, estimates of the number of seabirds by-caught annually in European waters (a mean of 195,000 individual birds, with a range of 130,000 to 380,000). These authors pinpointed the North-East Atlantic as the region with the highest by-catch, and gillnet fisheries as responsible for the highest by-catch levels, while highlighting significant knowledge gaps concerning the eastern Atlantic, the Mediterranean Sea and the Black Sea.

Phillips and others (2024) reviewed the global incidental mortality of seabirds in trawl fisheries, conservatively

estimating that 44,000 birds are caught every year, with albatrosses, large petrels and northern gannets being the most affected species. The authors agreed with others that the actual mortality is likely to be much higher, given the extent of cryptic mortality and poor or non-existent monitoring (Brothers and others, 2010).

The potential impact of mesopelagic fisheries on seabirds should also be regarded as an emerging concern (Dias and others, 2019). Mesopelagic species (i.e. those inhabiting depths of 200–1,000 m) are considered one of the most promising future human food resources (e.g. Webb and others, 2010) and several countries are exploring the viability of exploiting these species. Mesopelagic species potentially have enormous importance in the global ocean through their fundamental role in marine food webs and their function as biological carbon pumps, which helps to mitigate climate change (e.g. St. John and others, 2016). Recent studies have shown that the diets of several seabird species, including members of the most threatened groups (e.g. procellariiformes and penguins; see Wapp and others, 2017; Watanuki and Thiebot, 2018; Alho and others, 2022), are largely composed of mesopelagic species, raising concerns about the potentially devastating consequences of unregulated mesopelagic fisheries on seabirds and broader marine biodiversity.



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4. Responses to pressures on seabirds

Incidental fisheries by-catch remains one of the major threats to seabird species despite decades of understanding of the nature of the problem and the mandatory use of by-catch reduction measures by all tuna regional fisheries management organizations (RFMOs). This is particularly true for longline fisheries, which pose high risks to seabirds. Parties to international multilateral instruments such as the Convention on Biological Diversity have also committed to halting adverse impacts on threatened species, including impacts attributed to fisheries by-catch. However, the global target has not yet been met (Secretariat of the Convention on Biological Diversity, 2020). Therefore, long-term responses to seabird conservation challenges, especially those related to cross-border and high-seas threats, should be focused on improved monitoring and compliance with by-catch mitigation measures by members of RFMOs. For example, the Agreement on the Conservation of Albatrosses and Petrels has established a by-catch working group that evaluates current by-catch rates across fisheries, examines mitigation solutions, and provides best practice advice to RFMOs and others. It is recommended that those organizations update their seabird by-catch mitigation requirements to reflect the current best practice advice under the Agreement. In addition, the Commission for the Conservation of Southern Bluefin Tuna is implementing a multifaceted seabird conservation initiative funded by the Common Oceans Program Tuna Project (2023–2026) specifically targeting its members. Despite these efforts, the implementation of scientifically proven mitigation measures in regional fisheries management organizations remains slow.

Aside from addressing fisheries, several intergovernmental organizations are funding seabird conservation projects and/or actively supporting national Governments in implementing actions tackling major threats. Examples include programmes for controlling and eradicating invasive species (particularly mammalian predators such as cats and rodents) in key seabird colonies, as well as initiatives to minimize the impacts of light pollution. Furthermore, specific guidance has been provided by the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals on reducing known key pressures on seabirds such as light pollution (resolution 13.5, and the International Light Pollution Guidelines for Migratory Species), avian influenza (resolution 14.18), climate change (resolution 12.21), disturbance (especially as a result of tourism; see *International Guidelines for Sustainable Marine Wildlife Interactions: Boat-Based and In-Water Activities*) and harvesting in West Africa (see resolution 14.15, on the Action Plan to Address Aquatic Wild Meat Harvests in West Africa). In addition, guidance has been provided on conservation actions to reduce seabird vulnerability to climate change in the North-East Atlantic (Häkkinen and others, 2023) and on strategies to mitigate the impact of offshore wind farms on seabirds (Croll and others, 2022).

5. Knowledge gaps

Although seabirds are a relatively well-studied group of birds, there are still some major knowledge gaps. Some groups are poorly known due to their small sizes, nocturnal behaviour and breeding habits (e.g. burrow nesters such as storm petrels and other small petrels), making population estimates and trends for most of these species unreliable.

Another priority is to understand the population-level effects of pollution, overfishing, offshore wind farms and climate change in addition to the cumulative effect of these threats and those causing direct mortality of seabirds (such as by-catch, predation by invasive species, diseases, hunting and egg harvesting). Regarding diseases, particular attention should be paid to managing the spread and impact of HPAI. Due to its novelty, basic understanding of transmission dynamics and basic epidemiological characteristics (such as mortality rates and levels of post-infection immunity) is lacking in most regions but is critical for predicting the recovery and long-term viability of seabird populations.

Knowledge of seabird ecology still comes mostly from temperate and polar regions, while seabirds inhabiting tropical areas have received considerably less attention, particularly with respect to their at-sea distributions, especially in the Pacific Ocean (Carneiro and others, 2024).

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Subchapter 4H
Marine plants

Key points

- Marine plant species are spreading poleward due to climate heating, with mangroves encroaching into salt marshes.
- Restoration has established marine plants in small areas but not at a scale to match historical losses; preservation of existing marine plants provides many benefits.
- Rates of mangrove loss have slowed as policies to conserve and maintain existing mangroves are beginning to work. Some losses have been offset by low biodiversity reforestation projects.
- Sabkha plants, not covered in previous World Ocean Assessments, are overlooked but form important marine wetland ecosystems in arid and semi-arid regions.

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1. Introduction

Vascular marine plants create biodiverse habitats providing goods and services that are essential for achieving the Sustainable Development Goals (sect. 4, subchaps. 5G–5I; see also table 1 below). There are 72 seagrass species, and their diversity is highest in the tropical Indo-Pacific. Some meadows have several seagrass species, but most are monospecific. *Thalassodendron pachyrhizum* is the deepest living marine plant and occurs down to 63 m depth (Martin and others, 2023). Mangrove diversity and extent peaks in tropical Asia with 69 species (and 13 hybrids) that belong to 18 families that include trees, shrubs, palms and ferns (Leal and Spalding, 2024). *Rhizophora mangle* is the most common mangrove tree species worldwide. Salt marshes occur from the tropics to the Arctic, with over 500 known species, including grasses, shrubs and herbs (Adam, 2016; Fitzgerald and Hughes, 2021). Sabkhas are often used for salt extraction (Alshenawy and others, 2021; Ghazanfar, 2024), and their flora (e.g. *Atriplex*, *Salicornia, Salsola* and *Suaeda* species) tolerate high salinity, freshwater scarcity and extreme temperatures, with adaptations that include succulence, salt secretion and osmoregulation (Flowers and Colmer, 2008; Chenchouni, 2017).

Table 1
Global legal and policy instruments applicable to marine plants

Category	Instrument
Marine biological diversity	United Nations Convention on the Law of the Sea (1982)
	Convention on Biological Diversity (1992)
	Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (2023)
Wetlands	Convention on Wetlands of International Importance especially as Waterfowl Habitat (1971) (Ramsar Convention)
Natural heritage	Convention for the Protection of the World Cultural and Natural Heritage (1972)
Trade in endangered species	Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (1973)
Climate	United Nations Framework Convention on Climate Change (1992)
Shipping	International Convention on the Control of Harmful Anti-fouling Systems on Ships (2001)
	International Convention for the Control and Management of Ships' Ballast Water and Sediments (2004)
Life below water	Sustainable Development Goal 14 (2015) (non-binding)

Source: Prepared by the writing team.

2. Environmental change since the second *World Ocean Assessment*

Changes in overall status

Seagrasses

Twenty-two species are in decline due to the impacts of fishing, poor water quality, mariculture and coastal urban and industrial development (United Nations Environment Programme, 2020). Ten are Vulnerable, and *Phyllospadix japonicus* and *Zostera geojeensis* are Endangered (International Union for Conservation of Nature (IUCN), 2024). Some seagrass meadows suffer from overconsumption by herbivores such as sea urchins (subchap. 4F) or turtles in places where their numbers have grown locally thanks to conservation measures (subchap. 5G). Seagrasses can recover when pressures on coastal systems are reduced; *Halodule wrightii* and *Zostera japonica* are increasing (United Nations Environment Programme, 2020), although invasive species are a growing threat (Beca-Carretero and others, 2024). "Blue carbon" and the role of marine plants in the carbon cycle are explained in subsection 5B, chapter 1. The only seagrass blue carbon project is in the United States of America, where 3,151 ha of *Zostera marina* has been restored since the publication of the second *World Ocean Assessment*.

Mangroves

Although rates of loss have slowed since the publication of the second *World Ocean Assessment*, some species, such as *Bruguiera hainesii,* remain Critically Endangered (Bunting and others, 2022; IUCN, 2024; Leal and Spalding, 2024). A global campaign,[1] launched in 2022 and supported by 50 Governments, is aimed at protecting 15 million ha of mangroves worldwide. Some recent losses have been offset by restoration projects (Leal and Spalding, 2024; see also subchap. 5H), which are mainly focused on the following mangrove species: *Rhizophora mangle, R. mucronata, R. apiculata, Bruguiera gymnorhiza, B. cylindrica, Ceriops tagal, Avicennia germinans, A. marina* and *Laguncularia racemosa* (Verra Registry;[2] Plan Vivo;[3] Climate Action Reserve;[4] Clean Development Mechanism[5]). The biodiversity of these plantations is lower than in natural mangrove forests (Lovelock and others, 2024).

Salt marshes

These habitats are declining worldwide (for estimates of the rate, see subchap. 5I), often due to land reclamation, conversion to agriculture, increased erosion, sea-level rise, eutrophication (Roman and others, 2023; see also sect. 4, subchap. 5A) and invasive species (sect. 4, chap. 6). Salt marsh species are spreading polewards due to recent climate heating (Cavanaugh and others, 2019; Cohen and others, 2020) and planting and restoration work has been successful in some regions (Xiao and others, 2020; Liu and others, 2024).

3. Region-specific changes in biodiversity

Arctic Ocean

Zostera marina is the only seagrass reported in the Arctic. This region has approximately 17% of the global extent of salt marshes, with at least 113 species of vascular plants (12% of Arctic flora); information on recent changes in their status is lacking (Sergienko, 2013; Worthington and others, 2024) although the region is warming rapidly, which is expected to favour the northward spread of temperate marine plants but threaten those adapted to surviving seasonal freezing conditions.

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Phragmites australis has invaded western North Atlantic salt marshes; it is expensive and difficult to remove, but can provide ecosystem benefits (Macy and others, 2021). Extensive areas of the previously degraded seagrasses *Zostera marina, Ruppia maritima* (Chesapeake Bay) and *Thalassia testudinum* (Tampa Bay) have recovered in the United States of America thanks to reductions in nutrient pollution. *Avicennia germinans* and *Rhizophora mangle* mangroves are expanding northward in the western North Atlantic (Cavanaugh and others, 2019; Vervaeke and others, 2024).

Blue carbon projects in the eastern North Atlantic are using *A. germinans, A. africana, Laguncularia racemosa* and *R. mangle*. Sabkhas can provide habitat for a wide diversity of vascular plant taxa (from 29 families) including endemics, for example *Echiochilon simonneaui* and *E. chazaliei* (Qninba and others, 2020), and critically endangered species, for example *Limonium mucronulatum*, which is found only in Cyprus (Senni and de Belair, 2020).

Endemic *Posidonia oceanica* meadows are receding in the Mediterranean due to human impacts, although some meadows of this and *Cymodocea nodosa* are expanding due to implemented legislation and restoration (de los Santos and others, 2019; see also table 2) and the use of best practices in transplantation (Pergent-Martini and others, 2024). *Halophila stipulacea* has spread in the region and *H. decipiens,* first reported in the Mediterranean in 2018, is expected to spread (Gerakaris and others, 2020) raising calls for improved biosecurity to prevent the arrival of non-native species (Galil and others, 2017).

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1 See https://climatechampions.unfccc.int/the-mangrove-breakthrough/?gad_source=1&gclid=CjwKCAjw74e1BhBnEiwAbqOAjBCngKwmr0oHNiBIXR-4Q4o5hZVtPnGcksOzlOs2zbILIIDWI1IL8BoCgZoQAvD_BwE.

2 See https://verra.org/registry/overview/.

3 See www.planvivo.org/

4 See https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=111.

5 See https://cdm.unfccc.int/Registry/index.html.

Table 2
Regional legal instruments applicable to marine plants

Region	Instrument
Europe	Convention on the Conservation of European Wildlife and Natural Habitats (1979) (Bern Convention)
European Union	Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora
	European Union Marine Strategy Framework Directive (2008)
	Nature Restoration Law of the European Union (2024)
Baltic Sea	Convention on the Protection of the Marine Environment of the Baltic Sea Area (1974) (Helsinki Convention)
North-East Atlantic Ocean	Convention for the Protection of the Marine Environment of the North-East Atlantic (1992) (OSPAR Convention)
Mediterranean Sea	Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (1976) (Barcelona Convention)
South-East Atlantic Ocean	Convention for Cooperation in the Protection, Management and Development of the Marine and Coastal Environment of the Atlantic Coast of the West, Central and Southern Africa Region (1981) (Abidjan Convention)
Western Indian Ocean	Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region (1985) (Nairobi Convention)
Red Sea and Gulf of Aden	Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment (1982) (Jeddah Convention)
Caspian Sea	Framework Convention for the Protection of the Marine Environment of the Caspian Sea (2003) (Tehran Convention)
South Pacific Ocean	Convention on Conservation of Nature in the South Pacific (1976) (Apia Convention)
Caribbean Sea	Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region (1983) (Cartagena Convention)

Source: Prepared by the writing team.

South Atlantic Ocean and wider Caribbean

The main blue carbon species now being planted in this region are the mangroves *Laguncularia racemosa, Rhizophora mangle, Conocarpus erectus, Avicennia germinans* and *Rhizophora harrisonii.* Several mangrove species are at elevated risk of extinction in the Caribbean (IUCN, 2024). Collection of and commercial trade in *Rhizophora mangle* is regulated in the Caribbean (see table 2). In Brazil, 80% to 90% of mangroves are in protected areas and the species are listed as of Least Concern (IUCN, 2024). The mangroves *Avicennia germinans, A. schaueriana, Rhizophora mangle* and *Laguncularia racemosa* are all expanding southward, causing the loss of salt marsh *Spartina alterniflora*, *S. densiflora* and *Acrostichum* plants (Cohen and others, 2020). The mangrove *Sonneratia apetala* has been introduced from the Indo-Pacific (Eysink and others, 2023). The seagrasses *Halodule wrightii* and *Halophila decipiens* have expanded south by approximately 250 km in the twenty-first century due to climate heating. The South Atlantic has vegetated hypersaline tidal flats (locally called "apicuns" or "salgados") that are easily damaged by human activities (Albuquerque and others, 2014). The West African coast has one of the highest rates of recent mangrove plant loss worldwide, due to agriculture, urbanization and cutting wood to burn (Food and Agriculture Organization of the United Nations (FAO), 2023) as well as oil pollution and the spread of invasive nipa palm. The Calabar Protocol on Sustainable Mangrove Management to the Convention for Cooperation in the Protection, Management and Development of the Marine and Coastal Environment of the Atlantic Coast of the West, Central and Southern Africa Region (see table 2), adopted in 2019, establishes rules for the environmental protection and conservation of mangroves, as well as their use.

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Since 2018, the main species planted in blue carbon projects in this region are *Avicennia marina, Bruguiera*

gymnorhiza, Ceriops tagal, Rhizophora apiculata and *R. mucronata.* Sundarbans is the largest mangrove forest in the world (10,200 km^2) and a world heritage site. Here around 50% of the trees have been felled for timber and to create space for agriculture and shrimp farms. The forest is being rapidly altered due to sea-level rise (Intergovernmental Panel on Climate Change (IPCC), 2022). Salt-tolerant species are increasing and spreading (e.g. *Avicennia marina* and *Phoenix paludosa)* with no plans in place to allow for the natural inland retreat of mangrove plants (Khan and others, 2020). The Indian Ocean mangroves *Bruguiera hainesii* and *Sonneratia griffithii* are critically endangered (Nuevo-Diego and others, 2021; IUCN, 2024).

Around the Persian Gulf and the Sea of Oman, conservation and restoration has contributed to the expansion of mangrove plants (Milani, 2018; Erfanifard and others, 2022). In the Islamic Republic of Iran they are expanding with sea-level rise where landward margins remain unimpeded by coastal development (Hamzeh and Lahijani, 2022; Irani and others, 2024). Mangrove extent is now increasing in the Red Sea and the Gulf of Aden (Blanco-Sacristán and others, 2022) with *A. marina* plantations in Saudi Arabia, Egypt and the Sudan. Restoration of *A. marina, Bruguiera gymnorrhiza, Ceriops tagal* and *Rhizophora mucronata* mangroves is under way in Somalia, Mozambique, Madagascar, the United Republic of Tanzania and Kenya.

Middle Eastern coastal sabkhas host 12 marine plant families that form biodiversity hotspots and carbon sinks (Ghazanfar and others, 2019; Dar and others, 2022; Eid and others, 2023). Some are native to this region, such as *Arthrocnemum macrostachyum* and *Halopeplis perfoliata.* The few sabkha plants that have had their conservation status listed are categorized as of Least Concern (IUCN, 2024). Several types of sabkha plants are economically important (e.g. *Aeluropus lagopoides, Juncus rigidus*, *Phoenix dactylifera, Suaeda vermiculata*).

The first seagrass restoration initiative for this region was announced in 2024 to rescue and transplant eight Red Sea seagrass species. In the United Republic of Tanzania, best practices for the transplantation of *Syringodium isoetifolium* are being promoted (Wegoro and others, 2022). In Mozambique and South Africa, experimental transplantation of the regionally endangered *Zostera capensis* was recently achieved (Amone-Mabuto and others, 2022; Mokumo and Adams, 2023; Watson and others, 2023). In Kenya, there are attempts to restore the seagrasses *Thalassodendron ciliatum, Thalassia hemprichii, Enhalus acoroides* and *Syringodium isoetifolium*. Under the framework of the Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region (see table 2), detailed guidelines on seagrass and mangrove ecosystem restoration were published in 2020. Trial transplantations of *Thalassodendron ciliatum* and *Thalassia hemprichii* confirm that protecting existing meadows is more effective than planting new ones.

North Pacific Ocean

This region has around 250 to 300 salt marsh taxa, including species of *Suaeda*, *Triglochin* and *Salicornia;* some, such as *T. maritima,* are vulnerable (IUCN, 2024). Over 200 salt marsh plant species grow along the western North Pacific (Wang and Chen, 2013) where invasive *Spartina alterniflora* has colonized and altered 63% of the coastal marshes of China (Zhang and others, 2023; Liu and others, 2024). The use of *S. alterniflora* for coastal protection has threatened indigenous marine plants, birds, fisheries and tourism (Xia and others, 2021; Zhu and others, 2024) so it is now being removed; 68,000 ha had been removed in China by 2025, according to the Special Action Plan for Spartina Removal and Coastal Marsh Restoration (2022–2025) by the State Forestry and Grassland Administration of China. There has also been large-scale replantation of native species such as the mangrove *Kandelia obovata*, salt marsh plants such as *Suaeda salsa, Scirpus mariqueter* and the seagrass *Zostera marina* (Feng and others, 2017; Yang and others, 2024). Invasive *S. alterniflora* is also spreading in Japan and the Republic of Korea, where large-scale eradication projects are ongoing (Maebara and others, 2020; Kim and others, 2023; Matsuda and others, 2023; Koyama and others, 2024).

Climate heating has caused the recent northward expansion of the mangroves *Conocarpus erectus* in Mexico (Ochoa-Gómez and others, 2021) and *Kandelia candel* in Taiwan Province of China. Iriomote Island in Japan has 11 species of mangrove plants and nearly 70% of the national mangrove area (Inoue and others, 2022). Here, species include *Kandelia obovata*, *Bruguiera gymnorrhiza* and *Rhizophora stylosa*, which are conserved well in a natural world heritage site (United Nations Educational, Scientific and Cultural Organization (UNESCO), 2021; see also table 1). Some mangrove species are at an elevated threat of extinction along the North Pacific coasts of Central America (IUCN, 2024). China, home to 37 mangrove species, is reversing habitat loss with the

Government's Special Action Plan for Spartina Removal and Coastal Marsh Restoration (2022–2025), which is aimed at the planting of over 8,800 ha of new forest and restoring 8,200 ha of mangroves (Ouyang and others, 2024). Restoration efforts also include rare and endangered species like *Lumnitzera littorea*, *Sonneratia hainanensis* and *S. ovata* (Zhang and others, 2021).

Zostera, Ruppia and *Phyllospadix* seagrasses are widely distributed in the North Pacific, where they are under pressure from some of the most densely populated areas in the world (Su and others, 2020; Xu and others, 2021). Species such as *Zostera caespitosa, Phyllospadix iwatensis* and *Halophila beccarii* are listed as vulnerable (Yoshida and others, 2019; Du and others, 2023; Zhou and others, 2023; IUCN, 2024). In the eastern North Pacific, eel grass decline has been exacerbated by marine heatwaves, sea star wasting disease, reduced water clarity and physical damage from human activities such as boating and coastal development (Christiaen and others, 2022; Nahirnick and others, 2020). Similarly, between 2015 and 2021, over 1,000 ha of *Zostera japonica* were lost in the Yellow River estuary in China due to *Spartina alterniflora* invasion and typhoons; restoration efforts are aimed at mitigating this damage (Zhou and others, 2023; Liu and Ma, 2024).

South Pacific Ocean

Improved water quality has resulted in recent regrowth of the seagrasses *Posidonia australis* and *Posidonia sinuosa* (Fernandes and others, 2022). *Avicennia marina*, the only mangrove species in New Zealand, is expanding south throughout the South Pacific, encroaching upon salt marshes (Whitt and others, 2020). In Australia, subtropical and temperate coastal salt marsh plants are threatened (IUCN, 2024), but taxa are being conserved and recovered, such as *Sarcocornia quinqueflora*, *Suaeda australis* and *Sporobolus virginicus* (Beaumont and Dittman, 2022; Rankin and others, 2023). *Posidonia australis* restoration has worked in small areas (Sinclair and others, 2021), but not yet at a scale to match historical losses. *Zostera chilensis* is considered endangered in the South-East Pacific.

Note: there are no marine plants in the Southern Ocean.

4. Key remaining knowledge and capacity gaps

Much of what is known about changes in marine plants worldwide comes from remote sensing. A lack of in situ monitoring, due to a lack of marine botanists and funding, means that there are knowledge gaps regarding the status of marine plants in most regions, with sabkhas especially overlooked. Molecular techniques have been developed for marine plant identification, but the infrastructure and human resources to do this work is lacking in many regions. The resilience of most marine plants to changing climate and ocean conditions has not been assessed.

Increased protection of marine plants requires international attention, support and cooperation. Marine plants provide biodiversity and ecosystem function support and coastal protection, and contribute to livelihoods and improved water quality (Macreadie and others, 2019). In some areas, mangroves have been so damaged that these services have been lost and the habitats have become a source, rather than a sink, of greenhouse gases (Bruederle and Hodler, 2019; Romero-Uribe and others, 2022). Criticisms of carbon markets largely centre around the integrity and additional benefit of carbon credits and certification schemes (Guizar-Coutiño and others, 2022; West and others, 2020; Comte and others, 2023). Assessments of carbon stored by marine plants present difficulties in submersed ecosystems (Macreadie and others, 2022; Niner and Randalls, 2021). Many blue carbon projects depend on philanthropy, rather than carbon credit finance; the viability of carbon finance for marine plant conservation is a current knowledge gap.

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Subchapter 4I
Macroalgae, not including phytoplankton

Key points

- Rapidly warming oceans, combined with anthropogenic stressors, will lead to further significant losses of certain macroalgal species and changes in the distribution patterns of others.
- The distribution of temperate and warmer-water species is likely to shift poleward into temperate boreal and deeper waters, conditional on dispersal capacity and substrate availability.
- The incidence of invasive macroalgal blooms and turfs is likely to increase, leading to changes in ecosystem function.
- Less than 1% of macroalgal species described to date have been evaluated for their extinction risk using the International Union for Conservation of Nature (IUCN) Red List of Threatened Species assessment, and nearly 76% of the 99 macroalgal entries on the List are Data Deficient. This significant gap poses substantial challenges for assessing risk status.
- Significant gaps in taxonomic and distribution knowledge for many macroalgae are impeding progress in the effective monitoring of changes in population size and geographical range.

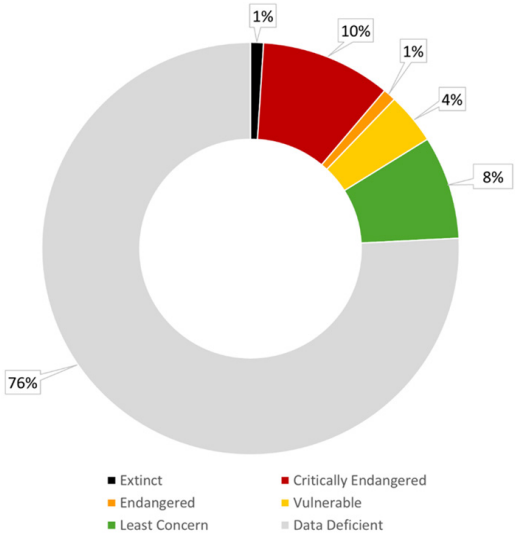
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1. Introduction

The present subchapter contains a presentation of the overall status of red, green and brown macroalgae (commonly known as seaweed) and changes in the period 2018–2024. Here, the macroalgae are considered in their own subchapter, having been considered as a food source and as an ecosystem in the first *World Ocean Assessment* and included with marine plants in the second *World Ocean Assessment*. Up to 2024, only 99 macroalgae, from a total of over 11,400 species described (Guiry, 2024) are included in the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2024), and 76% of these are categorized as Data Deficient (figure I). Recognizing macroalgae in the third *World Ocean Assessment* is, therefore, timely and critically important, given that the maximum potential area of ocean that seaweeds can occupy is an estimated 6 million to 7 million km^2 (Duarte and others, 2022). Seaweeds also play a crucial role in marine ecosystem functioning, and many species are being significantly affected by climate change and other anthropogenic stressors (Cottier-Cook and others, 2023).

Figure I

Categorization of 99 macroalgal species on the International Union for Conservation of Nature Red List, reported from the Pacific north-west, the Pacific south-east and the Pacific south-west



Source: Prepared by the writing team.

Note: No macroalgal species in other marine regions have been categorized on the IUCN Red List.

2. Environmental change since the second *World Ocean Assessment*

Changes in overall status

Red macroalgae

Red macroalgae (Rhodophyta) occur from the poles to the tropics and from the intertidal zone to 290 m deep (Littler and others, 1991). Most red macroalgae are marine (97%) (Sutherland and others, 2011); they are habitat-forming (e.g. rhodolith beds; see figure II) and are integral components of other habitats (e.g. coral reefs and temperate and Arctic rocky reefs) (see sect. 4, subchap. 5D). Red macroalgae provide ecosystem services, including by serving as breeding, spawning and nursery grounds for ecologically and commercially important marine species (Rendina and others, 2022). They are also harvested and/or farmed, primarily in South-East Asia for their gelling and emulsifying colloidal agents and in East Asia for food and aquaculture feed (Cottier-Cook and others, 2021) (see subsect. 5A, subchap. 1D). The maximum potential area for red macroalgae globally is estimated as 6.69 million km^2 (Duarte and others, 2022), including 4.12 million km^2 of rhodolith beds (Fragkopoulou and others, 2021).

Currently (as of 2024), 7,698 red macroalgal species have been described (Guiry, 2024), although high levels of (pseudo-)cryptic diversity mean that many still need to be described and that new species are continually being discovered (Leliaert and others, 2018). Since the publication of the second *World Ocean Assessment*, two new orders have been established, Corallinapetrales (Jeong and others, 2021) and Inkyuleeales (Díaz-Tapia and others, 2019). Many larger genera (e.g. *Pyropia*) have been split into smaller units to better reflect their evolutionary relationships (Yang and others, 2020) and many species have been moved between genera on the basis of recent research (Hughey and others, 2020).

The role of coralline red algae in carbon sequestration remains contested, as the calcification process also releases CO_2. New research suggests that coralline macroalgae recycle 40% of the carbon from calcification into photosynthesis (Mao and others, 2024). Given the longevity of coralline macroalgae and the extent of rhodolith beds, globally they could represent an important store of carbon (400 to 38,000 tons of carbonate deposits) (Schubert and others, 2024) (see subsect. 5B, chap. 1).

Figure II
Rhodolith (maerl) bed, Ireland



Source: Peter Tinsley.

Green macroalgae

Green macroalgae, most of which belong to the class Ulvophyceae (Chlorophyta), consist of 1,900 species and are distributed worldwide (El-Manaway and Rashedy, 2022). They are typically found in shallow waters, although species have been recorded at depths greater than 210 m (Littler and others, 1985). They provide a wide variety of ecosystem services, including an important food source for marine grazers, nutrient cycling and reef-building (e.g. *Halimeda* spp.). Although the total coverage of green macroalgae has not been estimated, the global coverage associated with soft or sandy and coral habitats is estimated at 1.2 million km^2 (McNeil and others, 2016). *Halimeda* species produce reef-like habitats (bioherms) and their carbonate production ranges from 0.8 to over 17,500 g per m^2 per year in the Indo-Pacific (Schubert and others, 2023). These habitats are now considered to be major contributors to carbonate production in tropical and subtropical regions (Schubert and others, 2023).

A few opportunistic *Ulva* species can form extensive blooms (known as "green tides"), which have increased in frequency and can cause biodiversity loss, health risks and a reduction in ecosystem services in the affected area (Smetacek and Zingone, 2013; Joniver and others, 2021). The introduced *Halimeda incrassata* has also spread rapidly in shallow subtidal habitats of the western Mediterranean Sea (Verbruggen and Ballesteros, 2024).

Progress in resolving evolutionary relationships in green macroalgae is continuing. Since the publication of the second *World Ocean Assessment*, studies have indicated that not all green macroalgae of the class Ulvophyceae may descend from a common evolutionary ancestor (Del Cortona and others, 2020; Hou and others, 2022). Bryopsidales is likely to be more closely related to Chlorophyceae, a class of predominantly freshwater green microalgae, than to the remaining Ulvophyceae.

Several studies focused on local diversity of green macroalgae have highlighted the discovery of many undescribed taxa (Lagourgue and others, 2022; Tran and others, 2022), particularly in tropical regions. The sequencing of *Ulva* types has resulted in several name changes (Hughey and others, 2020; Hughey and others, 2021, Gabrielson and others, 2024), with *U. fenestrata* being the correct name of the temperate species often reported as *U. lactuca*, and *U. lactuca* being the correct name for the pan-tropical *U. fasciata* (Hughey and others, 2019).

Brown macroalgae

The brown macroalgae or Phaeophyceae (Ochrophyta) provide several ecosystem services, including food and habitat provision, nutrient cycling and carbon fixation, with an estimated value of approximately 500 billion dollars globally (Eger and others, 2023). The number of brown macroalgal species has been estimated at 1,800 (Guiry, 2024), with the vast majority inhabiting the marine environment. Their distribution is global, although they are mainly temperate and polar species, except for *Sargassum* and species from the order Dictyotales, which are often abundant in the tropics. They occur from the intertidal zone to a depth of 30 to 40 m, although they can extend down to depths greater than 200 m (Žuljević and others, 2016). The overall estimate of the total potential area for brown macroalgae based on distribution models is 2.68 million km^2, including 0.13 million km^2 for the intertidal zone (Duarte and others, 2022), 2.5 million km^2 for subtidal zone (Gattuso and others, 2006), and a maximum of 6,000 km^2 for floating *Sargassum* species (Wang and others, 2019; Zhang and others, 2019). The latter includes more than 20 million tons of floating *Sargassum* extending from West Africa to the Gulf of Mexico (Wang and others, 2019).

Since the publication of the second *World Ocean Assessment*, a novel brown macroalgal genus and species, *Setoutiphycus delamareoides* (Ectocarpales), has been described in Japan (Kawai and Hanyuda, 2021). Numerous other new species have also been described, including 15 new *Lobophora* species (Sun and others, 2021; Vieira and others, 2021; Jurejan and others, 2024) and two new species of *Dictyota* (Win and others, 2024).

Eger and others (2023) recently estimated that six major forest-forming kelps (*Ecklonia, Laminaria, Lessonia, Macrocystis, Nereocystis* and *Saccharina*) sequester 4.9 million tons of carbon from the atmosphere annually. Increased understanding of the role of brown macroalgae in the carbon cycle has also yielded new global estimates for seaweed-derived particulate carbon export below a depth of 200 m, which total 3% to 4% of the ocean carbon sink capacity and correspond to the sequestration of 4.4 to 48.5 million tons of seaweed-derived carbon annually for 100 years (Filbee-Dexter and others, 2024).

Major threats

Changes in climate and the rapidly warming ocean (Intergovernmental Panel on Climate Change (IPCC), 2023), together with anthropogenic stressors such as overharvesting, eutrophication, ocean acidification and pollution, are predicted to lead to an unprecedented decline in many macroalgae species. Conversely, the incidence of certain macroalgal bloom-forming species and turfs is likely to increase (Filbee-Dexter and Wernberg, 2018; Bermejo and others, 2023; Feng and others, 2023) (figure III). Since the publication of the second *World Ocean Assessment*, reports have warned, however, that ocean warming, thermohaline and circulation change, and marine heatwaves, combined with other anthropogenic stressors, have resulted in the loss of more than 90% of certain kelp species in regions of Australia, the United States of America and Mexico, with significant implications for associated biodiversity and local economies (Dalmau and others, 2024). By the year 2100, depending on the warming scenario, brown seaweeds are predicted to lose 6% to 11% of their present estimated global coverage (Manca and others, 2024), and calcified red algal distribution is estimated to decline by 26% to 44% (Fragkopoulou and others, 2021), the latter being more susceptible to threats such as ocean acidification than the brown seaweeds (Cornwall and others, 2021). Furthermore, due to their extremely slow growth rates (around 1 mm per year), rhodolith beds may take centuries to millenniums to recover from damage and are consequently described as a non-renewable resource (Barbera and others, 2003).

Seaweed loss is also predicted to increase in tropical regions (e.g. tropical red algae in South-East Asia) due to the effects of climate change and the associated pest, disease and invasive species outbreaks (Brakel and others, 2021) (see sect. 4, chap. 6), increased incidence of typhoons, ocean acidification (Page and others, 2022) and overharvesting (Mac Monagail and others, 2017). Ranges are also likely to shift further into Arctic, temperate boreal and deeper waters (Lebrun and others, 2022; La Guardia and others, 2023).

Figure III
***Ulva* species bloom in Songosongo, United Republic of Tanzania**



Source: Flower Msuya.

3. Region-specific changes

Arctic Ocean

Arctic macroalgae are experiencing significant changes due to rapid warming, declining sea ice and increased habitat availability. Many species, particularly brown and red macroalgae, are predicted to expand their distributional ranges northward from more temperate regions, with a predicted loss of existing high-latitude macroalgae occupying similar habitats (Bringloe, and others, 2022). It is also likely that the potential calcified algal coverage will decline in the region as increasing temperatures and lower pH levels reduce the ability of these algae to calcify (Chan and others, 2020).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Marine heatwaves in this region have led to a marked range-shift or population-level change in a number of kelp species, such as *Laminaria digitata*, which is predicted to undergo a poleward range contraction and experience declines in growth performance (Leathers and others, 2024). Declines in the fucoid *Fucus vesiculosus* and increases in the filamentous turfing algae *Pylaiella littoralis* and *Ectocarpus siliculosus* have been attributed to increased eutrophication in the Baltic Sea (Hall and others, 2024). In the Mediterranean Sea, *Fucus virsoides* has seen a significant decline (Descourvières and others, 2024), and species that favour warmer waters (i.e. invasive species from tropical and subtropical regions, e.g. *Rugulopteryx okamurae*) have increased and spread (Falace and others, 2024; Wesselmann and others, 2024) (see sect. 4, chap. 6).

South Atlantic Ocean and wider Caribbean

Increases in macroalgal cover on hard coral reefs have been reported in the Mexican Caribbean (Contreras-Silva and others, 2020) and in floating, invasive, "pelagic" *Sargassum* species, which have extended beyond the Sargasso Sea (see subchap. 5Q) (Wang and others 2019) and proliferated in the tropical Atlantic between West Africa, Brazilian oceanic islands (Pellizzari and others 2020) and South America (Robledo and others, 2021; Sissini and others, 2017) (see sect. 4, chap. 6).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

As in the Caribbean, more temperature-tolerant macroalgae are becoming increasingly dominant on coral reefs following incidences of coral bleaching (Gonzalez and others, 2024).

North Pacific Ocean

Twenty red macroalgal species are reported on the IUCN Red List for this region and all are endemic to the Republic of Korea (North-West Pacific). Of these species, 4 are categorized as Least Concern and 16 are categorized as Data Deficient (IUCN, 2024). The green macroalga *Codium spinulosum* (Bryopsidales) and three species of brown macroalgae are also endemic to the Republic of Korea (Yim and Won, 2023) and are categorized as Data Deficient (IUCN, 2024).

South Pacific Ocean

The IUCN Red List contains 58 red macroalgal species found in the South Pacific Ocean. They include one Extinct species from the South-West Pacific and 57 species from the South-East Pacific, categorized as Critically Endangered (6), Vulnerable (3), Least Concern (4) and Data Deficient (44) (IUCN, 2024). The brown macroalga *Nereia lophocladia* is endemic to New South Wales, Australia (Mamo and others, 2021), in the South-West Pacific, and two green macroalgal species, *Rhizoclonium robustum* (Cladophorales) and *Entocladia thivyae,* are both endemic to the Galapagos Islands in the South-East Pacific (Ruiz and Ziemmeck, 2013). All three species are categorized as Data Deficient (IUCN, 2024). Fifteen species of brown macroalgae from the South-East Pacific are thought to be endemic to the Galapagos and are categorized as Endangered (1), Critically Endangered (4), Vulnerable (1) and Data Deficient (9) in the IUCN Red List (IUCN, 2024).

Southern Ocean

Records have recently been compiled for this region, which include 151 macroalgal species (85 Rhodophyta, 34 Ochrophyta and 32 Chlorophyta) in Antarctica, in

the South Shetland Islands (Pellizzari and others 2023; Oliveira and others, 2020), King George Island and Adelaide Island (Nelson and others, 2022). Distributional shifts and a reduction in the endemism rate have been reported in this region (Pellizzari and others, 2017), and, according to a recent modelling study, there is a high potential for macroalgal expansion into this region as a consequence of climate change (Manca and others, 2024).

4. Key remaining knowledge gaps

Despite the substantial evidence showing that macroalgal species and their habitats are declining, significant numbers of species remain undescribed, undiscovered (Guiry, 2024) and/or inadequately protected or conserved. The lack of a sound taxonomic framework for identifying and monitoring species hampers efforts to determine their distribution, threats and changes to status (Brodie and others, 2023), as well as efforts to implement effective conservation, protection and restoration strategies. It also presents significant challenges for assessing species for the IUCN Red List, which can raise awareness and assist in the global conservation of a species, as clearly shown by the fact that less than 1% of macroalgae known are listed from a very limited number of regions globally. The contribution of many seaweeds (e.g. rhodolith beds and kelp forests) to larger-scale processes such as carbon sequestration (Schubert and others, 2024) also requires further investigation (Intergovernmental Oceanographic Commission (IOC-UNESCO), 2024). There is an urgent need, therefore, to (a) strengthen data-driven conservation efforts to ensure that losses in macroalgal diversity are halted and habitats restored whenever possible; (b) ensure that range shifts are reported and vulnerable species protected; (c) identify undescribed species using the latest molecular approaches; and (d) ensure that the role of macroalgae in large-scale ocean processes is more widely understood.

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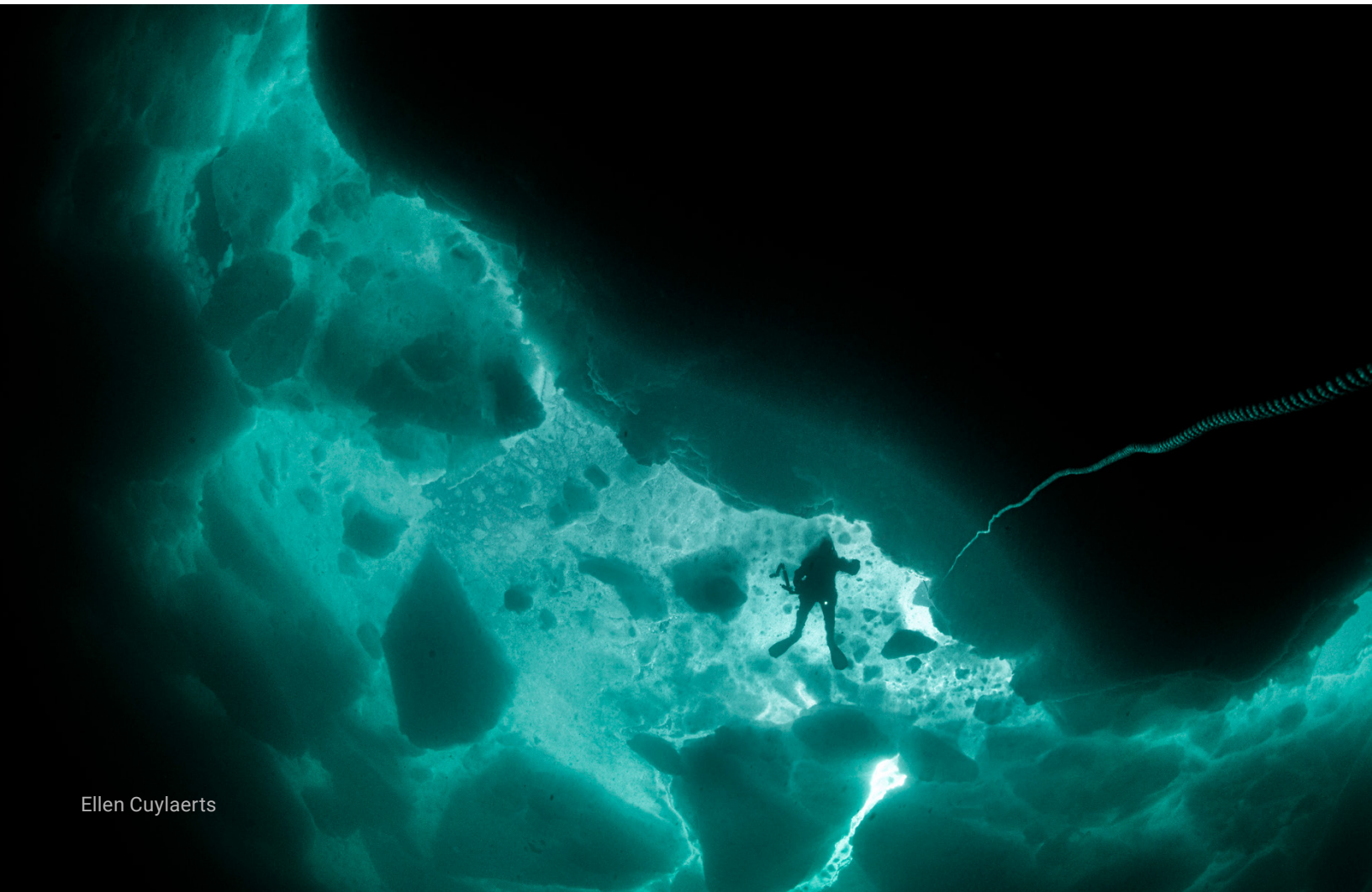
Chapter 5
Habitats



Ellen Cuylaerts

Introduction

The present chapter consists of 18 subchapters. It details the trends and state of a diverse range of marine and coastal habitats and ecosystems, providing insights into their characteristics, the changes they are undergoing and the pressures they face. Building upon the first and second *World Ocean Assessment* reports, it includes an examination of a wide range of marine habitats, from nearshore mangrove forests and salt marshes to the deepest trenches and seamounts. The change in state since the second *World Ocean Assessment* is provided in relation to mangrove forests, salt marshes, estuaries and deltas, rocky shores, seagrass meadows, cold-water corals, tropical and subtropical coral reefs, the Sargasso Sea, high-latitude ice, hydrothermal vents and cold seeps, and submarine habitats, such as seamounts, submarine canyons and trenches, and abyssal plains. The baseline state of each habitat established in the second *Assessment* serves as a reference point for examining changes over the past decade. Key threats to habitats have been identified and their influence on changes observed has been discussed. When information is available, specific regional changes have also been highlighted, and an outlook for habitats in the short to medium term has been discussed. In the present *Assessment*, a new subchapter is provided on fjord systems (sect. 4, subchap. 5R), including their ecological characteristics, as well as the effects of global warming and glacial changes. The chapter entitled "Open ocean" in the second *Assessment* has been renamed "Pelagic domain" (sect. 4, subchap. 5N) and covers its ecological zones and significance, and the threats posed by pollution and climate change. Given their widespread presence on hard substrates worldwide, sponges are now examined specifically in the subchapter on cold-water corals and sponges (CWCS). All of these ecosystems also face substantial anthropogenic pressures that are explored in greater detail both generally and within each subchapter. Notwithstanding the many challenges listed for each habitat type, efforts towards conservation and management are also discussed.



Ellen Cuylaerts

Subchapter 5A
Intertidal zone

Key points

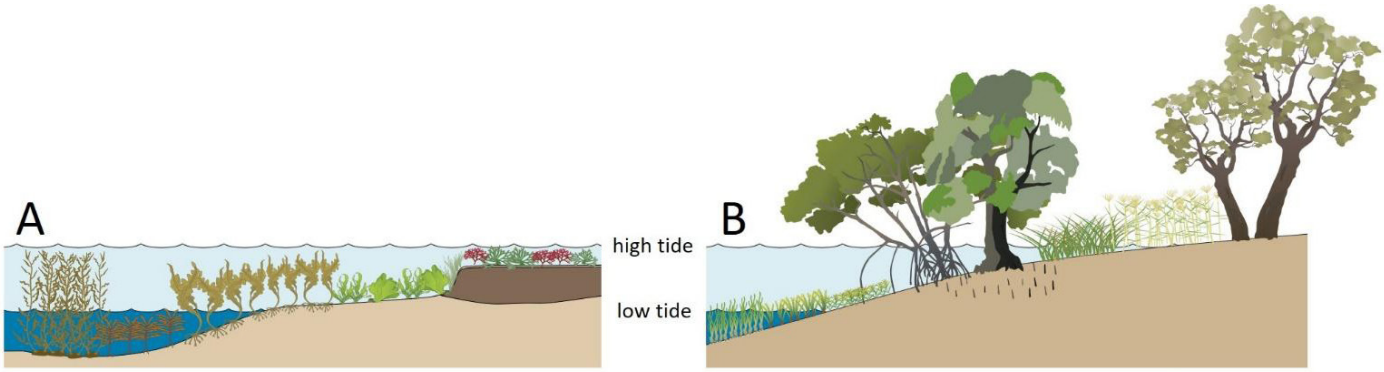
- The intertidal zone has undergone considerable transformations, driven primarily by climate change, pollution and coastal development. Sea level rise and coastal squeeze have led to habitat loss and reduced ecosystem services, such as the provision of natural resources and coastal protection. Rising temperatures and extreme weather events have exacerbated these effects.
- Efforts to integrate intertidal ecosystems into climate change mitigation initiatives and increased aquaculture activities have affected intertidal zones. Mangrove forests, salt marshes and seagrass beds are increasingly recognized for their role as blue carbon sinks, and there are initiatives to establish or re-establish and protect these habitats for their ecological and economic value.
- Regional differences in recent developments are becoming apparent, with each biogeographical region facing distinct challenges. Arctic areas are affected by sea ice retreat, while urbanization in such regions as the Mediterranean and the Caribbean is leading to eutrophication and habitat fragmentation. The vulnerability of intertidal ecosystems necessitates tailored conservation strategies that reflect regional socioeconomic and environmental contexts.
- Establishment and re-establishment efforts, such as introducing or restoring mangroves and seagrass and implementing green-grey infrastructure, are promising for mitigating habitat loss. The shift towards high-intervention approaches, such as ecosystem co-design, is aimed at creating resilient socio-ecological systems that adapt to climate change while providing essential ecosystem services.
- Rising carbon dioxide (CO_2) concentrations in seawater are resulting in ocean acidification that increasingly affects inhabitants of intertidal ecosystems, in particular molluscs, corals and other calcifying organisms.

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1. Introduction

The intertidal zone is a dynamic interface between marine and terrestrial environments, characterized by large environmental variability due to regionally specific tidal regimes. This boundary includes diverse habitats (see figure), such as rocky shores (with macroalgal forests), mudflats, seagrass beds, mangrove forests, salt marshes and sandy beaches, each providing essential services, such as shoreline stabilization, carbon sequestration (see subsect. 5B, chap. 1), and the provision of habitats for numerous species (Phang, Chou and Freiss, 2015).

Figure
Exemplary zonation of macrophytes in coastal and intertidal ecosystems



Source: Prepared by the writing team (symbols from ian.umces.edu/media-library).

Note: (A) temperate rocky shores: subtidal (e.g. *Macrocystis* spp., *Ecklonia* spp.), low-intertidal (e.g. *Laminaria* spp., *Lessonia* spp., *Ulva* spp.), mid-intertidal (e.g. *Chaetomorpha* spp.) and high-intertidal (e.g. *Chondrus* spp., *Codium* spp.) macroalgal beds (see sect. 4, subchap. 4I). (B) tropical and subtropical soft sediment shores: subtidal and intertidal seagrass beds (e.g. *Thalassia* spp., *Cymodocea* spp., *Halophila* spp.) (see sect. 4, subchap. 5G), mid- to high-intertidal mangrove forests (e.g. *Rhizophora* spp., *Avicennia* spp.) (see sect. 4, subchap. 5H), high-intertidal and low-supratidal salt marshes (e.g. *Spartina* spp., *Phragmites* spp.) (see sect. 4, subchap. 5I) and supratidal coastal forests (e.g. *Melaleuca* spp.).

The first *World Ocean Assessment* (United Nations, 2017) served to highlight the ecological significance of the intertidal zone, emphasizing its role as a unique interface between land and sea.

The second *World Ocean Assessment* (United Nations, 2021) contained details of substantial changes in intertidal ecosystems between 2010 and 2020, driven primarily by climate change, coastal development and invasion by non-native species. Key impacts included habitat degradation and biodiversity loss, notably in vegetated areas, such as mangrove forests, seagrass beds and salt marshes. These changes have affected the provision of ecosystem services and revealed the vulnerability of intertidal zones to anthropogenic pressures.

The present subchapter provides an updated assessment of the state of intertidal ecosystems between 2018 and 2023, detailing the effects of sea-level rise, pollution, habitat fragmentation and socioeconomic shifts. The importance of regional trends is discussed, as are establishment and re-establishment efforts and adaptive strategies, such as nature-based solutions and green-grey infrastructure, to address these challenges. The aim is to provide a comprehensive overview that supports policymakers in devising targeted conservation, establishment and re-establishment strategies, while promoting resilience through such approaches as ecosystem co-design (Zimmer, 2018; Zimmer and others, 2022) and community-based management. This approach aligns with Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

2. Environmental changes since the second *World Ocean Assessment*

Changes in overall status

Climate change and its consequences have become increasingly prevalent, and the pace of change is faster than anticipated, posing imminent and rapidly growing threats to coastal ecosystems. In addition to warming, sea-level rise has affected tangible change in intertidal habitats.

Between 2018 and 2023, sea-level rise accelerated, averaging 3.2 mm per year globally (National Oceanic and Atmospheric Administration (NOAA), 2024) and now exceeds 6 mm per year in regions such as South-East Asia, where land subsidence and glacial melt are exacerbating the effects (Idris and Munadi, 2022). Depending on topography, this rise either shifts intertidal habitats landward or compresses them against developed coastlines, resulting in "coastal squeeze" (Rilov and others, 2021). This reduces the extent of intertidal habitats along the tidal gradient, in particular in urban areas, and affects biodiversity and key ecosystem services, such as shoreline stabilization and carbon sequestration. As the sea level rises, coastal areas become ever more vulnerable to coastal erosion (Evelpidou, Tzouxaniot and Liaskos, 2022); this is especially true of coastal areas undergoing additional, non-climatic rises in sea level due to tectonic subsidence or other factors (Cai and others, 2022).

Among direct anthropogenic drivers, agricultural runoff and urban and industrial wastewater discharges are major contributors to eutrophication, causing harmful algal blooms and reduced oxygen levels in coastal waters (Tuholske and others, 2021). Heavy metals and hydrocarbons (see sect. 4, subchap. 6E) from industries affect sediment characteristics and benthic species and reduce biodiversity (Rahmanpour, Ghorghani and Lotfi Ashtiyani, 2014; Moazampour and others, 2021). Urban expansion has increased pollutants, such as microplastics (Chen and others, 2023), which accumulate in many marine organisms (von Hellfeld and others, 2022), and pharmaceuticals, potentially affecting the endocrine system of many organisms (Arguello-Pérez and others, 2019) (see sect. 4, subchap. 6E).

Those pressures notwithstanding, there has been intertidal habitat expansion in some areas due to natural processes. Areas with minimal human interference have experienced sediment deposition, due in part to sea-level rise and changed coastal hydrodynamics, leading to the formation of new mudflats and sandbanks (Wang and others, 2012). These new flats provide habitats for diverse species, enhancing local biodiversity. Such expansions are limited, however, to regions where natural sediment availability and transport are unaffected by human infrastructure (Braat and others, 2018).

Rising temperatures have affected, and continue to affect, the distribution of intertidal species and the species composition of intertidal communities. Warming has shifted thermally sensitive species polewards (Habary and others, 2017), and invasive species are often taking advantage of these conditions, outcompeting native species (Nguyen and others, 2020) (see sect. 4, subchap. 6A). The spread of invasive species is accelerated by global trade and travel (O'Shaughnessy and others, 2020). Along with rising temperatures, the frequency and severity of extreme weather events, such as storms and heatwaves, have increased (see subsect. 5B, chap. 4), contributing to ecosystem instability (Román and others, 2020).

Habitat fragmentation persists, especially in urbanizing regions of Asia and the Middle East, where natural intertidal areas are being replaced with artificial structures through land reclamation (Chee and others, 2017). This fragmentation reduces the ecological connectivity needed for species resilience (Aiken and others, 2021), leading to declining species richness, altered ecosystem processes and unequilibrated ecosystems (Sedano and others, 2021). There are some positive efforts to note, however. For example, green-grey hybrid infrastructure projects, in which mangroves and other natural elements are integrated into coastal defences, have mitigated erosion and created habitats that support intertidal species (Agardy and MacIntosh, 2023).

Significant socioeconomic changes can be attributed to environmental pressures, climate change (Mieszkowska and others, 2021), and conservation, establishment and re-establishment strategies (Katsanevakis and others, 2020) in the intertidal zone.

In response to declining shellfish populations, aquaculture (subsect. 5A, subchaps. 1C and 1D) has been focused increasingly on regional species better adapted to local environmental conditions (Carranza and zu Ermgassen, 2020). This reduces the impact of non-native species that often disrupt communities and ecosystems (Lima and others, 2018). Supporting native aquaculture improves sustainability and provides a stable income, contributing to food security and economic resilience (Engle and van Senten, 2022). Integrated and multi-trophic aquaculture

has gained in popularity. It involves combining different species, ideally of different trophic levels, of commercial interest in order to optimize resource use and reduce environmental impacts (Barrington and others, 2008). For example, farming filter-feeding molluscs improves water quality (reduced nutrient load) and light conditions for primary producers (Du and others, 2023). Including mangroves in shrimp aquaculture also enhances coastal resilience by reducing erosion and improving water quality (Mahmudi and others, 2022), thereby combining some of the many services and benefits of mangroves with food production. This approach aligns with global sustainability goals and offers new economic opportunities for coastal communities (Hossain, Senff and Glaser, 2022).

The recognition of intertidal ecosystems, such as mangrove forests, salt marshes and seagrass beds, as important blue carbon sinks has led to efforts to protect, establish or re-establish these ecosystems (Heimhuber and others, 2023). Integrating blue carbon valuation into coastal management has created incentives for conservation projects, potentially generating funding through carbon credits and international programmes (Friess and others, 2022), provided that proper monitoring, reporting and verification (MRV) are assured (Van Dam and others, 2024).

The socioeconomic impacts of rising sea levels and increased storm frequency highlight the need for effective coastal resilience strategies (Hoggart and others, 2014). Nature-based solutions, such as mangrove forest establishment and re-establishment and salt marsh conservation, have been prioritized for their role in enhancing biodiversity and providing coastal defence (Van Coppenolle and others, 2018; Van der Meulen and others, 2023). These approaches can be complemented by engineering solutions, including sea walls, to improve infrastructure (Burcharth and others, 2015). Such green-grey hybrid infrastructure, combining natural elements with technical, architectural or engineering solutions, balances human needs with biodiversity conservation and the need for efficient coastal protection (Waryszak and others, 2021; Evelpidou and Spyrou, 2024).

Coastal tourism can have profound impacts on marine biodiversity (Alsaleh and others, 2023) and can cause the pollution of coastal sediments (Buzzi and others, 2022). Tourist activities on sandy beaches are often facilitated through the deliberate destruction of intertidal habitats (Evelpidou and others, 2022; Andriolo and Gonçalves, 2023) or the removal of beach wrack, gravel, boulders and beach rocks, resulting in changed coastal morphodynamics and increased erosion (Johnston and others, 2023; Saitis, 2022). Coastal tourism has, in turn, faced challenges due to beach erosion, pollution and biodiversity loss, reducing the natural appeal of intertidal and coastal areas (Thinh and others, 2019). This can lead to a decline in tourism revenue, pushing communities to adapt by promoting conservation-focused or ecotourism initiatives (Lukoseviciute and Panagopoulos, 2021). These adaptations provide new income opportunities and raise awareness of the importance of preserving intertidal ecosystems (Harahab and others, 2021) for both tourists and local actors.

Community-based management of coastal resources has gained emphasis, in recognition of the fact that Indigenous, traditional owner and local community knowledge and stakeholder engagement and involvement are key to sustainability (Tetelepta and others, 2023). Empowering communities to co-design measures to manage fisheries, establish or re-establish ecosystems and participate in conservation programmes has been effective in building coastal resilience. These participatory approaches foster a sense of ownership, leading to better stewardship (Galappaththi and others, 2022).

3. Region-specific changes

Intertidal zones across biogeographical regions have experienced distinct trends driven by changing climatic conditions, socioeconomic factors and human activities. The following paragraphs provide an overview of key trends in the seven major biogeographical regions.

Arctic Ocean

In the Arctic Ocean, the rapid retreat of sea ice due to increasing temperatures has had a significant impact on intertidal habitats (Assis and others, 2022). Rising sea levels and storm frequency have led to coastal erosion, altering sediment patterns and affecting species reliant on stable intertidal environments (Jones and others, 2009). The northward expansion of sub-Arctic species has displaced native Arctic organisms, challenging Indigenous Peoples and communities who depend on intertidal resources (Stafford and others, 2022). Increased commercial shipping traffic due to receding sea ice has

led to higher pollution levels, including oil spills and noise pollution, disrupting intertidal ecosystems and wildlife (Ghosh and Rubly, 2015).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The North Atlantic, Baltic Sea, Black Sea, Mediterranean and North Sea regions have shown varied trends. The North Atlantic and North Sea face extreme weather events, floods of greater frequency and severity, and erosion (Mendez-Tejeda and others, 2020), while warming in the Mediterranean has facilitated invasive species, challenging native communities (Yeruham and others, 2020). Coastal urbanization in the Baltic (Vigouroux and others, 2021) and Black Seas (Akkoyunlu, 2018) has led to eutrophication, decreasing water quality.

South Atlantic Ocean and wider Caribbean

In the South Atlantic and wider Caribbean, coastal development (subsect. 5A, chap. 9), especially in urban areas, has fragmented mangrove and seagrass habitats (Blanco-Libreros and Ramírez-Ruiz, 2021). Tourism infrastructure expansion has further contributed to habitat loss (Tuholske and others, 2017).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

The Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf face intense socioeconomic and anthropogenic environmental pressures. Mangrove forests have been negatively affected by coastal squeeze (Milani, 2018), and increased temperatures have had an impact on intertidal ecosystems (Rajalakshmi and Achyuthan, 2021).

North Pacific Ocean

In the North Pacific, warming waters have shifted species distributions, facilitating invasive species (Liu and others, 2022). Coastal urbanization (Momota and Hosokawa, 2021), anthropogenic activities (Yap and others, 2020) and increased storm activity pose threats (Kuwano-Yoshida and others, 2022), leading to habitat fragmentation and highlighting the need for resilient construction practices (Bulleri and Chapman, 2010).

South Pacific Ocean

The South Pacific, which includes many island nations and small island developing States, has been affected by rising sea levels, leading to the loss of critical habitats and ecosystems, such as mangrove forests (Zhu and others, 2021), that are vital for communities dependent on small-scale fisheries (Flores-Verdugo and others, 2014). Pressures from urban expansion, pollution and habitat loss have caused the degradation of salt marshes and coastal wetlands, affecting both coastal biodiversity and the livelihoods of artisanal fishers (Gaete and others, 2017).

Southern Ocean

The Southern Ocean has seen less direct human influence (Murphy and others, 2021) than other regions, but climate change remains a major driver of environmental and ecological change and the degradation of intertidal habitats and ecosystems, as increased temperatures have altered species distributions in Antarctica (Chelchowski and others, 2021).

4. Key remaining knowledge and capacity gaps and new gaps

The ongoing trends in anthropogenic impacts, such as coastal development (see subsect. 5A, chap. 9), pollution (see sect. 4, subchap. 6E) and resource extraction, continue to degrade intertidal habitats (Stamp and others, 2022). At the same time, opportunities exist for the establishment and re-establishment of intertidal ecosystems in degraded and newly emerged habitats. Establishment and re-establishment efforts, however, must balance species richness, functional diversity and species distinctiveness in order to ensure that these ecosystems remain ecologically robust and contribute effectively to biodiversity, ecosystem processes and coastal resilience (Lester and others, 2020; Rahman and others, 2021, 2024).

Intertidal ecosystems exhibit a decline in native species richness (Cappelatti and others, 2020), and functional diversity and distinctiveness are being increasingly affected by the proliferation of invasive species (Pires-Teixeira and others, 2021) (see sect. 4, subchap. 6A). As species composition changes, the dynamic equilibrium of these ecosystems (Krohs and Zimmer, 2023) is at risk, potentially undermining their ability to provide essential services, such as shoreline stabilization, nutrient cycling

and carbon sequestration (Pinto and others, 2014). The success of measures to combat the spread of invasive species will depend on increased awareness of the threats they pose and on adequate training of staff in the authorities responsible (Roussos and others, 2021).

Conventional restoration methods, which focus on returning ecosystems to their original state, may be insufficient in the face of accelerating climate change and ongoing anthropogenic pressures (Capon and Pettit, 2018). High-intervention approaches, such as ecosystem co-design (Zimmer, 2018; Zimmer and others, 2022), are gaining traction. These methods are aimed at creating resilient socioecological systems that mitigate and adapt to the effects of climate change while serving human needs. Such strategies integrate natural and artificial components in order to bolster ecosystem services (Westphal and others, 2022).

The outlook for intertidal ecosystems ultimately depends on policy integration and effective management practices that combine conservation, establishment, re-establishment and adaptive approaches (Baskent, 2020). Engagement with stakeholders, in particular local actors and communities, and the incorporation of Indigenous knowledge, will be crucial for developing strategies that sustain these vulnerable, yet vital, ecosystems amid ongoing environmental challenges (Ndonye and others, 2021).

Key knowledge gaps with respect to the intertidal zone reflect the need for improved models and scenarios that can be used to project the future state of protected and established and re-established areas experiencing ongoing climate change effects (Garner and others, 2023). Such models must incorporate both physical and biological variables in order to predict how establishment and re-establishment actions will fare against accelerating sea-level rise and shifting climatic conditions. Reliable projections are crucial for ensuring the long-term sustainability of intertidal conservation efforts and for informing adaptive management strategies (Judge and others, 2018).

A significant capacity gap is the lack of widespread, standardized monitoring of biodiversity loss and species distribution shifts. The implementation of advanced techniques, such as molecular taxonomy and environmental DNA approaches, is essential to fill this gap. These methods allow for non-invasive, accurate monitoring of species composition and help to detect changes, especially in response to climate-induced shifts in distribution, providing critical information for conservation planning (Thomsen and Willerslev, 2015). Actions against future coastal squeeze, such as strategic spatial planning for coastal vegetated ecosystems, require further research and implementation (Lester and others, 2020). Learning from such examples as New Orleans, United States of America, where proactive spatial planning has resulted in the designation of areas for future coastal vegetated ecosystems, can help to mitigate habitat compression (de Mutsert and others, 2021). Such strategies must be adapted to regional contexts in order to ensure the preservation and resilience of intertidal habitats (Chambers and others, 2019).

Addressing these gaps requires coordinated international and regional efforts (Cavallo and others, 2016), increased funding for technological advances and capacity-development initiatives (Clark and others, 2018) to empower local communities and stakeholders to use modern tools and approaches for effective intertidal ecosystem management (Goodspeed and others, 2016).

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Subchapter 5B
Biogenic reefs and sandy, muddy and rocky shore substrates

Key points

- Sandy, muddy and rocky shores, biogenic reefs and other coastal habitats are crucial for biodiversity and ecosystem services, supporting economic activities and protecting coastlines.
- Coastal habitats are interconnected by ocean currents that form part of a meta-ecosystem, in which energy and organisms can move across boundaries, enhancing ecosystem resilience. As such, integrated management approaches are needed.
- These habitats face intense pressures from climate change and human activity, with warming temperatures and heatwaves, rising sea levels, coastal hardening and pollution affecting biodiversity and ecosystem functions.
- The loss and degradation of coastal habitats pose a range of threats to human well-being, from increased flooding risks to loss of livelihoods in tourism and fisheries.
- Addressing these challenges demands robust governance, scientific innovation, strong partnerships and enhanced ocean literacy to promote and conserve resilient, sustainable coastal ecosystems.

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1. Introduction and context

The present subchapter is focused on four critical coastal habitats (sandy, muddy and rocky shores and biogenic reefs), highlighting their ecological and economic importance. These environmental systems support diverse species that contribute to water filtration and nutrient cycling and play an important role in the coastal food chain. In addition, biogenic reefs, formed by such organisms as corals, oysters and mussels, provide natural barriers against coastal erosion. Home to invaluable natural resources, these coastal habitats are essential for tourism, fisheries and recreation, underscoring their economic, social, cultural and ecological significance.

Understanding these habitats requires recognizing the fact that they are interconnected through a "meta-ecosystem", in which energy, materials and organisms move across habitats, shaping their resilience and health. This spatial connectivity necessitates collective management rather than isolated approaches in order to ensure the persistence and functionality of these habitats (Vozzo and others, 2023).

These coastal habitats face a multitude of stressors, however, driven primarily by local human activity and climate change. Urban expansion, pollution and climate-induced impacts, such as rising sea levels and heatwaves, are degrading biodiversity and ecosystem functions (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), 2024). These cumulative stressors pose significant challenges to the resilience, conservation and sustainability of these ecosystems.

The present subchapter provides an updated assessment of biogenic reefs and sandy, muddy and rocky shores, with a focus on the changes observed since the second *World Ocean Assessment.* Emphasis is placed on the need for integrated coastal management to support biodiversity functions and the sustainable use of marine resources, which includes guaranteeing equitable access to coastal resources.

2. Changes in the state of biogenic reefs and sandy, muddy and rocky shore substrates

In the past decade, biogenic reefs and sandy, muddy and rocky shores have undergone increased landscape transformations due to a mix of environmental and anthropogenic pressures. Climate change and local anthropogenic impacts are driving transformations that threaten the stability and functionality of natural habitats (Hatje and others, 2024). Bivalve-based biogenic reefs illustrate this point; oyster reefs faced centuries of extraction, and estimates suggest that 85% have been lost globally, with impacts on socioecological systems (Beck and others, 2011; Thurstan and others, 2020). Mussel reefs have faced similar historical declines due to overharvesting, replacement by invasive species and, more recently, climate change, leading to scientific mussel reef restoration efforts (Petraitis and Dudgeon, 2020; Roberts and others, 2023; Buschbaum and others, 2024). These reefs play a vital role in coastal ecosystems by filtering water, attenuating waves, stabilizing sediments and providing habitats for a variety of species. Rising sea levels, increasing air and water temperatures, increased pollution and nutrient run-off, however, are leading to hypoxic conditions that weaken reef structures and reduce biodiversity. The harvesting of oysters and mussels, if unmanaged, further diminishes reef resilience, leading to long-term declines in water quality and biodiversity (Ponti and others, 2021; Gianni and others, 2023).

Urbanization stressors, including population density, tourism, nocturnal light, urban infrastructure, vegetation changes and certain beach nourishment practices, significantly reduce species richness and biomass on sandy and muddy shores (Orlando and others, 2020; Corte and others, 2022; De Schipper and others, 2024) and can also have impacts on the nesting areas of migratory animals, such as marine turtles. Artificial light at night disrupts key ecological processes, including circadian rhythms, feeding, reproduction and migration, affecting biodiversity, increasing the vulnerability of species and altering predator-prey dynamics (Marangoni and others, 2022). In addition, recent studies have shown that coastal squeeze and human infrastructure already affect 33% of global beaches, with up to 26% at risk of severe sand loss by the end of the century, compromising resilience to sea-level rise (Vousdoukas and others, 2020; Nawarat and others, 2024). Combined pressures from sea-level rise and urbanization are shrinking intertidal

zones, affecting dependent species and reducing vital ecosystem services, such as coastal protection, recreation and habitats for shorebirds (Defeo and others, 2021; Lansu and others, 2024). Conserving natural areas and applying nature-based solutions can reduce infrastructure impacts by up to sevenfold (Lansu and others, 2024; Nawarat and others, 2024).

Muddy shores, which are found in estuaries, bays and other sheltered areas, are vital as nursery habitats for fishes, feeding grounds for migratory birds and sites of high nutrient cycling. They are, however, highly vulnerable to sedimentation changes caused by natural events, such as storms, and human activities, such as dredging and coastal construction. Increased sedimentation can smother benthic communities, disrupt nutrient dynamics and degrade habitat quality. Large-scale infrastructure, such as hydropower stations and reservoirs, reduces sediment and water flow, leading to seawater backflow, salinization and declines in marine biodiversity (Yi and others, 2023). Pollution from agricultural run-off and urban waste introduces nutrients and toxins, creating hypoxic zones that further harm biodiversity (Daramola and others, 2022; Popoola, 2022). In addition, urban infrastructure, such as seawalls and breakwaters, replaces natural habitats with hard substrates, which can facilitate biological invasions and species range expansions (Airoldi and others, 2015; Dong and others, 2016; Wang and others, 2020).

Sea-level rise has a significant impact on rocky shores and biogenic reefs by submerging intertidal areas, resulting in less biodiverse submerged communities and diminished ecosystem services, such as net production and biodiversity (Rilov and others, 2021). Changes in wave energy further affect these ecosystems; for example, high-energy environments reduce oyster density and surface area, decreasing species diversity (Vozzo and others, 2021). Climate change is also altering community composition on rocky shores, with warming waters affecting the range of intertidal and subtidal species (Sanford and others, 2019; Smale and others, 2019; Krumhansl and others, 2024). Heatwaves and other extreme events cause mortality in temperature-sensitive species, such as forest-forming kelps, transitioning communities to low-lying macroalgal turfs or filter feeders, and increasing the abundance of warm-tolerant species (Filbee-Dexter and Wernberg, 2018; Smith and others, 2021; Weitzman and others, 2021). Seasonal species loss can also occur in tropical monsoonal areas. These shifts reduce ecological resilience, increasing vulnerability to disturbances and facilitating the establishment of invasive species under heat stress (Diez and others, 2012; Rilov and others, 2021; Weitzman and others, 2021).

These soft- and hard-bottom interconnected habitats are influenced by the exchange of energy, nutrients and organisms across their boundaries, forming what is known as a meta-ecosystem (Loreau and others, 2003). It is still uncertain, however, how changes in one habitat type, such as a decline in biogenic reefs, can have cascading effects on adjacent habitats, such as sandy and muddy shores, altering nutrient flows and larval supply. This interdependence emphasizes the need for integrated management approaches in which the connectivity of natural habitats and the cumulative anthropogenic impacts on coastal ecosystems are taken into account, especially in the face of increasing global warming, since record air and ocean temperatures were reached in 2023 and 2024 (IOC-UNESCO, 2024).

3. Consequences of the changes for human populations, economies and well-being

The degradation of biogenic reefs and sandy, muddy and rocky shores has direct and indirect implications for human well-being. Natural habitats are crucial in providing multiple ecosystem services (such as coastal protection), supporting commercial fisheries and coastal livelihoods and offering opportunities to enhance local ecological knowledge and cultural values. As natural buffers, biogenic reefs protect coastal areas from wave action and storm surges, mitigate eutrophication through nitrogen removal and sequester significant amounts of carbon (Krause-Jensen and Duarte, 2016; Eger and others, 2023). The ecosystem services provided by kelp forests have been valued at $500 billion globally (Eger and others, 2023). With the weakening of these reefs due to human impacts and habitat fragmentation, communities face increased vulnerability to coastal hazards, resulting in higher costs for flood defence infrastructure and disaster recovery (Ponti and others, 2021; Giglio and others, 2024). Moreover, losses of kelp forests are associated with significant declines in fisheries revenues (Rogers-Bennett and Catton, 2019). Losses of macrophytes in soft sediment and rocky habitats reduce their capacity to sequester carbon, and sediment disturbance causes carbon emissions.

Sandy beaches attract millions of visitors annually, generating substantial revenue for local economies. The uncontrolled development of tourism and urbanization, however, is having an increasing impact on habitats. For example, the impacts of artificial light on coastal habitats require immediate attention, as artificial light reduces biodiversity and associated ecosystem services, such as sustainable fisheries and coastal protection. Indirect economic impacts include decreased fishery productivity and the degradation of tourism habitats (Marangoni and others, 2022). The loss of beach areas due to coastal squeeze and erosion also reduces their appeal, leading to declines in tourism revenue and job losses in the service sector, such that total revenue loss could reach €140,400 per m² per year (Alexandrakis and others, 2015). Moreover, increased litter, pollution and habitat degradation on popular beaches lowers their recreational value, affecting both quality of life for residents and the appeal to tourists (Harris and Defeo, 2022; Bozzeda and others, 2023).

For traditional and Indigenous communities, muddy and rocky shores provide critical resources, such as shellfish and seaweed, and hold cultural and spiritual significance. The degradation of these habitats threatens not only food security, but also cultural and natural heritage. Threats to the recreational gathering of intertidal resources can also have an impact on well-being (Morris-Webb, 2021). In many coastal regions, these communities are at the front line of climate change impacts, experiencing increased flooding, loss of land and displacement. This loss of traditional livelihoods and connection to natural landscapes can lead to psychosocial stress and the loss of cultural identity, affecting overall community well-being (Biedenweg and others, 2016; Bennett and others, 2023).

Human health may also be affected, with coastal degradation leading to increased exposure to pollutants and pathogens, particularly in urbanized areas where urban infrastructure increases the presence of anthropogenic litter and synanthropic species (e.g. rats), which are vectors of various pathogens (Aguilera and others, 2023). For instance, the decline in oyster reefs reduces water filtration capacity, increasing the concentration of harmful bacteria and pollutants in coastal waters. This compromises water quality, which is essential for such activities as swimming, fishing and shellfish harvesting, posing health risks to local populations (Fanini and others, 2020; Vousdoukas and others, 2020).

4. Key region-specific changes and consequences

Climate change and anthropogenic impacts are influencing habitats worldwide through both global and local drivers. This part of the subchapter provides examples of such impacts with reference to their geographic, climatic and socioeconomic context and highlights recent updates for the period 2018–2024.

Increased wave energy and extreme weather in the North-West Atlantic and North Sea are intensifying erosion and sediment transport, reducing biodiversity and habitat resilience on sandy and rocky shores. Coastal urban expansion is worsening these impacts by increasing pollution and weakening natural defences. In the United Kingdom of Great Britain and Northern Ireland, marine heatwaves have significantly reduced cold-water species, while winter storms have resulted in damage to habitats, including mussel and algae loss. Despite some recovery, climate change has driven shifts towards warm-affinity species (Mieszkowska and others, 2021). In the Gulf of Maine and eastern Canada, warming temperatures and heatwaves, overfishing and interactions with invasive species are causing declines in kelp abundance and shifts from cold- to warm-tolerant species (Suskiewicz and others, 2024; Krumhansl and others, 2024). Similarly, the heatwave in the Gulf of Alaska between 2014 and 2017 transitioned rocky intertidal habitats from macroalgae to barnacle- and mussel-dominated communities, reducing diversity and ecosystem complexity with lasting effects on productivity and trophic interactions (Weitzman and others, 2021).

Knowledge of the western region of the South Atlantic, in particular in Argentina and Brazil, has increased, but the east coast remains less studied. The western region faces significant coastal erosion, habitat alteration and ecological imbalances due to storms, cold fronts and disasters, such as oil spills and mine tailing discharges (Gutierrez and others, 2023; Escobar, 2019; Soares and others, 2020). These disturbances have an impact on tourism, fisheries and biogenic reefs with long-term socioeconomic effects. Key environmental drivers, such as ocean temperature, wave exposure and freshwater inputs, shape intertidal communities, altering species abundance and marine trophic chains – trends increasingly influenced by climate change (Pardal and others, 2021, 2022, 2023; Cordeiro and others, 2024). Excessive

fishing of herbivores, such as fish and sea urchins, has caused biodiversity loss and macroalgal overgrowth, while urban pollution and eutrophication promote opportunistic species, further degrading benthic ecosystems (Martinez and Altvater, 2024).

In the Indian Ocean region, rapid coastal development, including the construction of artificial islands, is disrupting natural sediment flows, harming coastal habitats. In such regions as Maldives, these modifications have altered fish migration routes and reduced access to traditional fishing grounds, affecting food security and local economies. Plastic pollution and illegal waste dumping from these developments are further degrading water quality, affecting biodiversity and human health (Honorato-Zimmer and others, 2022; McCabe, 2023). Marine heatwaves, in addition to regional warming, are causing widespread tropicalization of kelp forests (Zarco-Perello and others, 2017). The eastern and south-eastern Pacific coasts are strongly influenced by climate-driven upwelling systems critical for nutrient supply to sandy and rocky shores (Thiel and others, 2007). Shifts in wind patterns affecting upwelling intensity are disrupting ecosystem productivity, affecting fisheries and biodiversity. The region is also vulnerable to oceanographic events, such as El Niño, which exacerbate coastal erosion, flooding, seawater encroachment and ecosystem changes, leading to long-term socioeconomic challenges (Xiu and others, 2018; Gelcich and others, 2019). During the El Niño event of 2015–2017, species turnover was significant, with some migrating southwards due to temperature anomalies (i.e. changes in temperature relative to expected temperatures in the region), although latitudinal community structure remained largely stable (Valqui and others, 2021).

Arctic coastal erosion, driven by permafrost thaw and increased wave action from sea ice loss, is expected to accelerate significantly by the twenty-second century, especially under high-emission scenarios (Nielsen and others, 2022). This process threatens sandy and muddy shores by displacing sediments, altering nutrient dynamics and degrading habitat quality. It also releases significant amounts of organic carbon, contributing to greenhouse gas emissions, while jeopardizing infrastructure, biodiversity and ecosystem services, with erosion rates doubling in some warming scenarios. The productivity of macroalgae on rocky shores in the Arctic may increase as the climate warms due to reduced ice cover and greater climate suitability for some species (Filbee-Dexter and others, 2019), though declines in some cold-adapted macroalgal species are expected at the southern extent of their range (Li and others, 2024) or where turbidity increases due to ice melt (Filbee-Dexter and others, 2019).

5. Outlook, key remaining knowledge and capacity gaps and new gaps

Biogenic reefs and sandy, muddy and rocky shores face increasing pressures from climate change, urbanization and human exploitation, threatening their biodiversity and ecosystem services. Coastal population growth, land reclamation and infrastructure development disrupt natural processes, accelerate biodiversity loss and alter sediment dynamics (Vousdoukas and others, 2020; Luijendijk and others, 2018). Emergent threats, such as plastic pollution and artificial light at night, place further strain on these environments, requiring targeted research and mitigation strategies (Marangoni and others, 2022; Ford and others, 2022).

Innovative approaches, such as blue engineering, whereby eco-friendly materials are used in coastal defences, show promise for sustainable urban development that respects ecological integrity (Bugnot and others, 2018; Pinardi and others, 2024). Further research is necessary, however, to understand the long-term impacts of these approaches on meta-ecosystems in terms of reducing biotic homogenization and improving the interconnectedness of natural coastal habitats, with consequences for ecosystem resilience and biodiversity (Firth and others, 2024).

Incorporating traditional and Indigenous ecological knowledge, which offers place-based insights for sustainable management and restoration, into governance frameworks is vital (Strain and others, 2018; Stori and others, 2019; Haugan and others, 2024). Significant knowledge gaps persist, however, particularly regarding the cumulative impacts of multiple stressors, including terrestrial influences, on marine ecosystems. Improved monitoring systems, capacity-building and interdisciplinary research are crucial, especially in underresearched biodiversity hotspots, such as the South Atlantic, the wider Caribbean and South-East Asia (Coleman and others, 2019; Cruz-Motta and others, 2020; Muller-Karger and others, 2024). A socioecological approach, integrating natural and social sciences, is essential for

holistic coastal management and conservation (Arbic and others, 2024).

Promoting ocean literacy and raising public awareness of the socioeconomic importance of these coastal habitats through education, communication and cultural aspects, including all knowledge systems (Glithero and others, 2024), are key steps to enhance stakeholder engagement in conservation. Multilevel governance structures that include all national and community stakeholders can foster collaboration and ensure that policies reflect local realities. This participatory approach requires financial investment in capacity-building and technical training, enabling communities to actively manage and monitor their ecosystems.

For effective conservation and restoration, countries must develop equitable, inclusive and adaptive policies that prioritize the sustainable management of coastal habitats (Waltham and others, 2020) based on an understanding of their structural and functional connectivity. This includes securing long-term funding for the monitoring and restoration of natural habitats, the greening of artificial infrastructures to improve biodiversity and the use of nature-based solutions (Morris and others, 2018; Aguilera and others, 2020). Empowering communities and fostering resilience in these habitats allow countries to enhance the resilience of their coastal communities against climate change impacts, ensuring the protection of coastlines, the conservation of biodiversity and the sustainability of livelihoods (Sabine and others, 2024).

Safeguarding coastal habitats demands a robust form of governance that integrates diverse knowledge systems and encourages participatory decision-making. Innovative and extensive research is needed in tropical and subtropical regions, where data gaps persist; at the same time, it is important to address disparities in coastal management between high- and middle-income countries (Nawarat and others, 2024). Coordinated, well-financed strategies aligned with global initiatives, such as the 2030 Agenda for Sustainable Development and the United Nations Decade of Ocean Science for Sustainable Development, are essential to ensuring the resilience and sustainability of these ecosystems for future generations. Continued monitoring, research, local management and international cooperation are essential in order to adapt to evolving challenges and safeguard these invaluable natural resources.

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Subchapter 5C
Atolls and their lagoons and islands

Key points

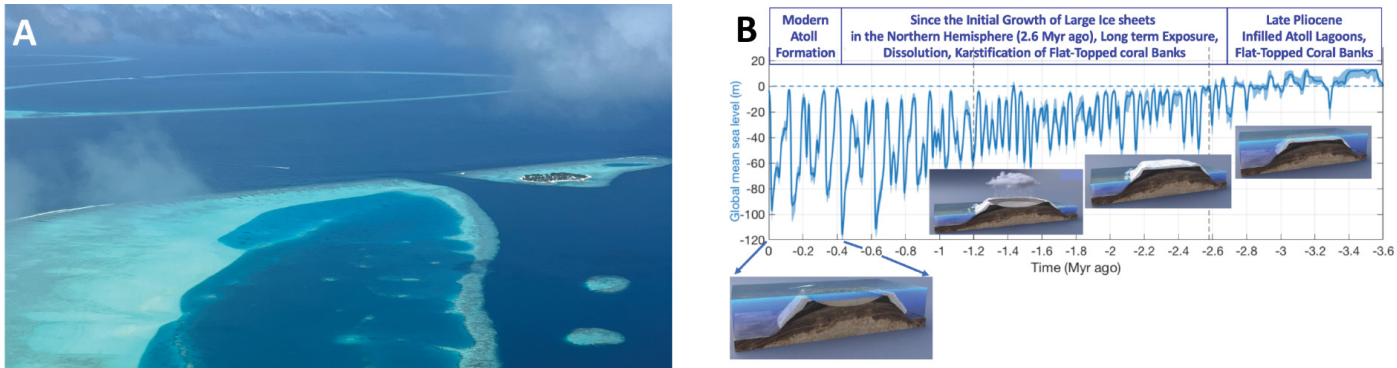
- New antecedent karst theory for the origin of atolls and atoll islands as an alternative to Darwin's subsidence theory.
- New concepts on the hydrogeology of atolls and atoll islands.
- Updated perspective on atolls and lagoons and tourism.
- Production of carbonate sands and sediment transport during anomalous storm events and its role in maintaining the sediment supply to atoll islands.
- Increasing alteration of the functioning of critical ecological processes on atolls by global and local stressors.
- Need for conservation measures for atoll ecosystems to be focused on reducing carbon dioxide (CO_2) emissions, enforcing marine protected areas (MPAs), promoting sustainable use, engaging communities and supporting research.

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1. Introduction

Atolls are ring-shaped coral reefs encircling lagoons, commonly found in tropical and subtropical seas (see figure I). Atoll islands are morphologically coherent wave-built accumulations of bioclastic sediment located on atoll rims or on patch reefs within atoll lagoons and emergent at all stages of the tide. Distant from continental influence, atolls are usually surrounded by abyssal depths, although their reef crests rise close to mean sea level and enclose lagoons that range from a few metres to 70 m deep (Purdy and Winterer, 2001). At a broader scale, the diameter of an atoll typically spans from a few kilometres to several dozen kilometres. Worldwide, there are some 268 atolls, with a further 171 subtidal atoll reefs with little or no island development (Goldberg, 2016). Lagoons are often euhaline, with ocean water being exchanged through reef passages or by means of indirect mechanisms, but many atolls in the Central Pacific have isolated lagoons that range from hypersaline to brackish or fresh. Atolls serve as habitats of global significance for tropical biodiversity, including seabirds, marine turtles and other keystone island species, while inhabited "atoll nations" serve as home to Indigenous Peoples and cultures (Steibl and others, 2024a, 2024b).

Figure I
Vattaru Atoll, Maldives (A) and improved antecedent karst theory for modern atoll origin (B)



Sources: (A) André W. Droxler and (B) https://cp.copernicus.org/articles/17/361/2021 and www.youtube.com/watch?v=J950wu7tsmw.

Note: (A) View towards the south-west, on a flight crossing the southern rim of Felidhe Atoll on 30 August 2023. Vattaru Atoll appears in the background (shown in light blue) with a coralgal rim fully enclosing its lagoon. In the foreground, the southern rim of Felidhe Atoll is displayed, consisting of a small atoll, referred to as Faro; Rakeedho Island formed behind the reef crest. (B) The graph shows sea-level fluctuations over the past 3.6 million years (modified from Berends and others, 2021); this framework can be used to explain the origin of modern atolls through the newly published improved antecedent karst theory (Droxler and Jorry, 2021). A series of schematic representations from a video produced by IFREMER (the French Research Institute for Exploitation of the Sea) display the evolution of a Late Pliocene flat-topped bank, through long-term exposure during the Quaternary, forming a karstic morphology characterized by a central depression bounded by a raised rim, which becomes the templet preferentially colonized by coral reefs during successive deglacial and highstand refloodings in the past 450,000 years.

2. Environmental changes since the second *World Ocean Assessment*

Further baseline information on atolls and their lagoons and islands can be found in the supplementary materials[1] and in chapter 7 of the first *World Ocean Assessment* and chapter 7C of the second *Assessment*. According to Darwin's "subsidence theory", atolls form as volcanic islands gradually sink, with coral growth keeping pace, creating a reef-ringed lagoon (Darwin, 1842; Davis, 1928). In contrast, according to the "antecedent karst theory" (Droxler and Jorry, 2021), atolls develop from pre-existing limestone karst topography, with dissolution and erosion shaping the reef structure before submersion. In essence, the emphasis of the former theory is vertical subsidence, while the emphasis of the latter theory is preformed karst landscapes serving as the foundation for atoll formation. "Antecedent karst theory" as an alternative to Darwin's "subsidence theory" is introduced as a new concept in the present *Assessment* that was absent from the previous Assessments. An updated perspective is also provided on the hydrogeology of atolls and atoll islands and the impact of tourism on atolls and lagoons. Further novel topics addressed in the present *Assessment* are the vulnerability of atolls and their fauna to sea level and climate change, along with response strategies and the role of ecosystem services, restoration, conservation, mitigation and adaptation.

Unique ecological functioning of atolls

Isolation from continental influence results in the reef ecosystems of atolls functioning differently from those of coastal reefs located on continental shelves. The absence of river discharges and the typical remoteness of atolls limit nutrient availability, making them highly oligotrophic (Hatcher, 1990; Ke and others, 2018). Primary production is thus more dependent on the photosynthesis performed by coral-associated Symbiodiniaceae dinoflagellates. Symbiodiniaceans are hosted intracellularly by corals and dependent primarily on nutrients provided by the host metabolism instead of the surrounding water (Davy and others, 2012). The remoteness of atolls also limits connectivity processes, as atolls have fewer nearby source populations than coastal reefs, making recruitment and population replenishment reliant on self-seeding and long-distance larval transport (Underwood and others, 2012). Likewise, isolation and the lower sediment input amplify the impact of bioerosive processes by such organisms as sponges, bivalves and urchins, which perforate the reef carbonate framework produced by hermatypic corals (Pari and others, 2002). As a result of these processes, the availability of sediment, nutrients and larval propagules on atolls is limited compared with that in coastal areas, making atolls more vulnerable to natural and anthropogenic disturbance.

Atoll vulnerability to anthropogenic stressors, including sea-level rise and climate change

Habitability is dependent upon the availability of safe land freshwater and food, as well as access to safe settlements and infrastructure and to sustainable economic activities (Duvat and others, 2017, 2021; Duvat, 2020). Multiple anthropogenic stressors affect atolls as a result of human activities or environmental changes at both the local and the global scale. Local-scale stressors include overfishing, unregulated tourism and coastal development (Knowlton and Jackson, 2008; McMichael, 2023). Overfishing is common, as local populations rely heavily on fisheries resources and can quickly deplete fish stocks (Newton and others, 2007; Wolanski and others, 2020). Unregulated tourism often results in trampling and anchoring on the reef, which damages the carbonate reef framework, while coastal and infrastructure development often results in habitat destruction and reef pollution (Hawkins and Roberts, 1993; Allemand and Osborn, 2019; Ríos and others, 2021; United Nations Environment Programme (UNEP), 2022). Increased waste discharge from residential and industrial activities leads to organic and inorganic contamination, plastic pollution and nutrient enrichment, promoting algal overgrowth and coral mortality across the reef (Sheppard and others, 2020).

Besides local-scale stressors, atolls and reef ecosystems in general are highly vulnerable to the two major global-scale stressors affecting environments worldwide, namely, global warming and ocean acidification, both of which are a consequence of increased CO_2 concentrations in the atmosphere and ocean. Increasing sea-surface temperatures and more frequent and intense marine heatwaves are by far the greatest threat to atolls and reef ecosystems. Corals under thermal stress undergo bleaching, which produces extensive coral mortality (Hughes and others, 2020), while ocean acidification greatly intensifies erosive processes in the atoll framework (Hoegh-Gudlberg and

[1] See https://zenodo.org/records/19262017.

others, 2007). In addition, with an increasingly energetic atmosphere, atolls are subject to intense wave action that threatens their structural integrity (McLean and Kench, 2015; Hynes and others, 2025).

Impacts on organisms, functional roles and ecological processes

Global warming, the main threat to reef environments, disrupts coral-dinoflagellate symbiosis in a phenomenon called "bleaching" (Glynn, 1996). Thermal stress triggers the excessive production of reactive oxygen species by dinoflagellates (Lesser, 2006). As an accumulation of reactive oxygen species overwhelms the antioxidant defences of the coral, it leads to cellular damage. Corals eventually expel their symbiotic dinoflagellates and the white calcareous skeleton becomes visible under the translucent tissue. Consequently, the absence of the photosynthetically derived carbon provided by the dinoflagellates leads to an energetic deficit, causing coral mortality (Anthony and others, 2007). Once corals perish, their bare skeleton is subject to erosion, further undermining reef integrity (Braz and others, 2022). Since 2018, numerous atolls worldwide, including those in Hawaii, the Chagos Archipelago, French Polynesia and Maldives, have experienced severe coral cover declines of up to 76% due to bleaching (Sheppard and others, 2020; Speare and others, 2022; Winston and others, 2022). The most vulnerable species are branching corals, especially *Acropora* spp., which play a key role in supporting biodiversity by providing habitat complexity (Richardson and others, 2017).

Ocean acidification is slowly producing its first impacts on coral reefs. Its main consequence is the impairment of the calcification process in corals, giant clams and other calcifying reef organisms. The CO_2 absorbed by the ocean reacts with water to form carbonic acid (H_2CO_3), which dissociates and releases a proton (H^+), thus lowering the pH. This proton binds with carbonate ions (CO_3^{-2}) and reduces its availability, thus inhibiting the production of calcium carbonate ($CaCO_3$) skeletons (Hoegh-Guldberg and others, 2007). This makes corals more susceptible to erosion from waves and boring organisms, ultimately reducing habitat complexity. Recent projections have shown that atolls in the Western and Central Pacific are among the most vulnerable to this process (Duvat and others, 2021).

Overfishing has also had a major impact on the functioning of atolls. One of the main symptoms of overfishing is a reduction in catch per unit effort, which is declining globally in reef environments (Eddy and others, 2021). Keystone species, such as sharks, groupers and parrotfishes, have experienced a significant recent decline on atolls in Belize, Maldives and Solomon Islands (Hughes and others, 2020; McClanahan and Muthiga, 2020; Skinner and others, 2020). Some of these species play critical roles in maintaining reef resilience; for example, herbivorous parrotfishes consume large amounts of turf algae, which are the main competitors of corals (Holbrook and others, 2016). Parrotfish removal contributes to the occurrence of phase shifts, where reefs transition from a coral-dominated to an algae-dominated state (Hughes and others, 2007). Likewise, the loss of higher trophic levels, such as predators, often leads to trophic cascades. Global and local stressors are thus altering the functioning of critical processes on atolls, including calcification, photosynthesis, competition and trophic interactions.



Ellen Cuylaerts

3. Region-specific changes

Arctic Ocean, North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean, North Sea and Southern Ocean

The Arctic Ocean, North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean, North Sea and Southern Ocean do not have atolls.

South Atlantic Ocean, wider Caribbean, Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden, Persian Gulf, North Pacific Ocean and South Pacific Ocean

Atolls are present across the world's ocean basins at low latitudes, but the vast majority (96%) of them lie in the Indian and Pacific Oceans, which have 56 and 367 atolls, respectively (Goldberg, 2016). Reef provinces are generally divided into three macroregions based on their biogeographical patterns: Indo-Pacific, Caribbean and South Atlantic. Exposure and vulnerability to global environmental change, however, are determined by a combination of biological factors, with contrasting atoll and island physical geomorphologies and degrees of socioeconomic development – from uninhabited and rural to urban islands (Duvat and others, 2017). All climate scenarios project a global increase in the intensity of cyclones and the frequency of intense El Niño/Southern Oscillation and Indian Ocean Dipole events (Intergovernmental Panel on Climate Change (IPCC), 2019) that will affect atolls in all ocean basins. There are important spatial variations in exposure to climate risk, however, with atolls in the western Pacific subject to a more rapid increase in risk compared with those in the Central Pacific and Indian Oceans (Duvat and others, 2021).

The responses and resilience to these stressors vary significantly among reef provinces (Roff and Mumby, 2012; Duvat and others, 2021). Coral bleaching disparities have been observed, with South Atlantic reefs, which are typically dominated by massive, stress-tolerant corals, experiencing less bleaching than those in the Indo-Pacific and Caribbean (Mies and others, 2020). Rocas Atoll, the only atoll in the South Atlantic, experienced minimal coral mortality despite record-breaking thermal stress in 2019 (Gaspar and others, 2021). In the Indian Ocean, reefs on the remote atolls of the Chagos Archipelago recovered to net accretion within two to six years after mass bleaching episodes associated with El Niño/Southern Oscillation events (Lange and others, 2023). Conversely, the densely populated atolls of Maldives took approximately 15 years to reach a similar degree of recovery and accretion (Carruthers and others, 2024). This underlines the need for a holistic and spatial planning-based approach to improve coral reef recovery on atolls because each one will respond in a unique way.

Increasing seawater temperature and acidification, coupled with rapid rates of sea-level rise, may alter the oceanographic dynamics and biological functioning of atolls. This may enhance erosive processes and lead to the inundation of low-lying islands, resulting in multiple territorial and social challenges for island nation communities. Atoll islands are subject to changes in their size and position due to both anthropogenic and natural causes, and one of the most pressing questions is whether they are currently gaining or losing land. A recent study of land area changes in 221 atolls in the Indo-Pacific between 2000 and 2017 showed a net land mass gain (Holdaway and others, 2021). It should be noted, however, that these increases, which are more common on atolls located in the South China Sea and Maldives, resulted mostly from land reclamation rather than natural processes. McLean and Kench (2015), Kench and others (2022) and Kench and others (2024) investigated shoreline change on 244 islands in the past 30 years, during which the sea level rose at an average rate of 3 mm/year. Contrary to the prevailing narrative of inundation, erosion and outmigration (Dickinson, 2009; McMichael, 2023; Weatherill, 2023; Tierolf and others, 2023), the evidence shows that island area is generally expanding due to sediment accretion.

Critical to the future preservation of atoll islands is the maintenance of sediment supply (Tuck and others, 2021), both in situ through the production of carbonate sands and by sediment transport during anomalous storm events through reef crest-sediment apron pathways. Sediment consolidation and binding are regulated by vegetation and soil development, influenced by rainfall patterns, wind exposure (Steibl and others, 2024a, 2024b) and the aeolian supply of non-carbonate material and guano, which enhance soil productivity (Browning and others, 2023; McTainsh and Strong, 2007; D'Amico and others, 2023) (see figure II).

Rising sea levels will also result in lateral intrusion of saltwater. On islands with a dense human population, this stress is superimposed on salinization from overabstraction of groundwater and aquifer contamination (Ferguson and Gleeson, 2012; Werner and others, 2013;

Michael and others, 2017; Sawyer and others, 2016). In some areas, including the western part of the Micronesian group of islands, the effects of sea-level rise may be mitigated in part by increased freshwater recharge due to higher rainfall in the coming decades, but islands in other areas will experience increasing drought influenced by natural climatic cycles, such as the El Niño and La Niña phases of the El Niño/Southern Oscillation phenomenon (Der Velde and others, 2006; Bailey and others, 2021). Changes in tidal and wave energy and morphological changes due to coastal erosion during storm surges will also negatively affect the volume of fresh groundwater (Briggs and others, 2021; Stanic and others, 2024).

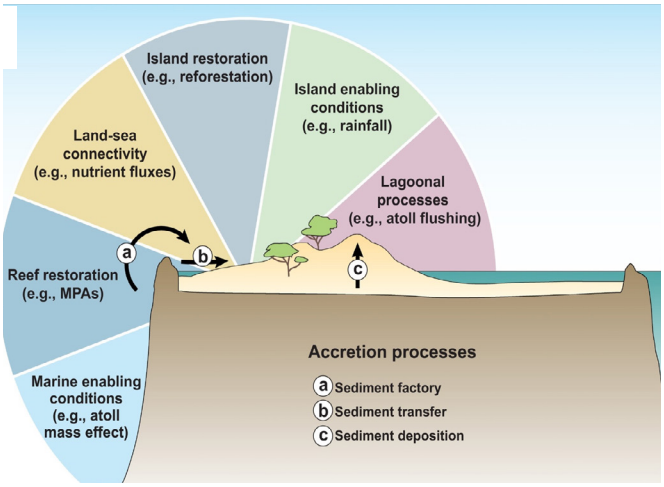
In addition to a rise in mean sea level, the freshwater lens is vulnerable to salinization due to seawater inundation during extreme storms. Saltwater can infiltrate through the vadose zone, as well as through open boreholes, trenches and karst shafts, which provide direct access to the aquifer; saltwater can continue to infiltrate after the storm surge, sourced from seawater ponded in surface depressions (Holding and Allen, 2015). According to numerical simulations, the degree of aquifer salinization due to overwash is largely determined by vadose zone thickness, but it is the recharge rate that determines recovery times (Holding and Allen, 2015). These range from 1 year to 19 years after a single overwash event. The non-linear interactions between wave-driven flooding and sea-level rise will lead, by the middle of the twenty-first century, to annual overwash of most atoll islands, causing widespread erosion and loss of potable water (Storlazzi and others, 2018). Combined with the effects of tidal fluctuations on the mixing of an increasingly thin freshwater lens with underlying seawater, inundation will detrimentally affect the ecological sustainability, agricultural productivity and human habitation of atoll islands.

Another critical issue is the appeal of atoll islands to tourists, which arises in part from the perception of lagoons as pristine and tranquil destinations. For instance, surveys conducted in Maldives revealed that 65% of tourists consider environmental quality a critical factor in their choice of lagoon destinations (UNEP, 2022). Environmental degradation and overcrowding can tarnish this image, diminishing atoll islands' attractiveness to future visitors. Maintaining a positive destination image requires balancing the development of tourism with conservation efforts to ensure that lagoons retain their natural beauty and ecological health. Nonetheless, lagoons remain highly attractive destinations, often creating a trade-off between preservation and visitation.

Tourism-related activities commonly exert pressure on lagoon ecosystems. The development of infrastructure, such as hotels, restaurants and marinas, can lead to habitat destruction and fragmentation. For instance, the construction of coastal resorts often involves dredging and land reclamation, which disrupt lagoon hydrodynamics and sedimentation patterns (Pinto and others, 2020). Data indicate that over 50% of mangroves in some lagoon regions have been lost to tourism infrastructure (Gómez-Vega and Herrero-Prieto, 2018). Furthermore, direct tourism activities, such as diving and snorkelling, as well as boat anchoring and trampling, cause additional erosion and also interfere with trophic interactions from the lagoon to the reef (Diedrich, 2007; Renfro and Chadwick, 2017). Pollution is another critical concern. An influx of tourists can result in elevated levels of solid waste and wastewater, often exceeding the natural assimilative capacity of lagoons. This can lead to eutrophication, characterized by algal blooms, oxygen depletion and fish kills (Martínez and others, 2019).

While tourism can boost local economies by creating jobs and generating revenue, it can also lead to sociocultural changes (Everett and others, 2018). The commercialization of lagoon areas may marginalize local communities, who often depend on these ecosystems for traditional livelihoods, such as fishing and aquaculture. Furthermore, overcrowding during peak tourist seasons can strain local infrastructure and reduce quality of life for residents.

Figure II
Identification of biogeosphere links critical for atoll island protection and restoration



Source: Steibl and others, 2024b.

4. Key remaining knowledge and capacity gaps and new gaps

Response strategies and the role of ecosystem services

Although reducing greenhouse gas emissions is essential, the magnitude of physical and chemical changes already embedded in climate and ocean systems indicates that the proper implementation of adaptation strategies to enhance resilience is crucial to ensuring the survival of atoll islands. Anomalous storm events can have a positive effect on the sediment balance of an atoll island, where shoreward sediment transport leads to coastal accretion, and bleaching events can result in periods of enhanced sediment generation (Perry and others, 2020, 2023). It is more often the case, however, that storm-driven coastal erosion and sediment export have a negative (and potentially catastrophic) effect (Storlazzi and others, 2018; Georgiou and others, 2024). Superimposed on these effects are the negative environmental and social impacts of tourism, which must be balanced against the economic benefits that it can bring. Adaptation strategies, including the establishment of effective MPAs and no-take zones and the promotion of ecotourism practices that minimize environmental footprints (UNEP, 2022), should be adopted.

Efforts are under way to control seawater intrusion along some continental margins through the construction of engineered barriers, such as cut-off walls and subsurface dams, which physically limit the hydraulic connectivity between the aquifer beneath the island and the saline aquifer offshore (Chang and others, 2022; Zheng and others, 2022; Fang and others, 2023). This is likely an impractical solution for most low-lying atoll islands, but comparable impoundment of freshwater within a Pleistocene karstified island aquifer has been shown to result from a coastal mantle of lower-permeability Holocene grainstone (Whitaker and Smart, 2004). This highlights the risks of construction and dredging that threaten the integrity of such natural barriers, especially for islands growing by lateral accretion. The focus should be directed towards developing approaches to minimize the effects of washover on the freshwater lens.

The effectiveness of responses to climate-driven challenges on atoll water supply depends on abundance and demand. Traditional rainwater storage tanks can support low demand but quickly become depleted, especially during droughts (Wallace and Bailey, 2015). Enhanced aquifer recharge and underground storage schemes are generally preferable to more high-cost options, such as seawater desalination, especially for smaller communities, but remain vulnerable to seawater inundation and contamination. In contrast, atoll island cities and tourist developments can more readily benefit from technological advances allowing potable water to be supplied at an increasingly low cost (Shokri and Fard, 2023).

While climatic factors cannot be controlled locally, the retention of sediment on islands can be supported through ecological interventions, such as reforestation, forest diversification and the removal of invasive species, as well as appropriate management of agricultural activity and human infrastructure engineering (Duvat and others, 2017; Steibl and others, 2024a, 2024b). Mangrove swamps, seagrass beds and other coastal ecosystems have high organic carbon storage capacity in biomass and soil (Macreadie and others, 2021). There is a need to preserve and to enhance this "blue carbon" storage, as well as restore biodiversity and the other benefits of the services provided by coastal and shallow marine ecosystems (Twomey and others, 2024; Hagger and others, 2024). Nature-based solutions are more sustainable and widely applicable to the diverse range of challenges facing non-urbanized atolls. It has been strongly suggested that the key to unlocking these solutions is linking ecosystem-based interventions that span marine and terrestrial zones with processes of sediment production and accretion of atoll islands (Steibl and others, 2024a, 2024b). The success of such a programme depends heavily on prior planning and design, effective monitoring, evaluation and reporting and post-implementation maintenance (Standards Reference Group (SERA), 2018). On urbanized atolls, such as Malé in Maldives and Majuro in the Marshall Islands, however, the timescales involved render nature-based solutions largely unviable. The raising of atolls and the construction of coastal defences are the types of intervention being implemented at present in such capitals as Funafuti and Majuro (Esteban and others, 2019). Moreover, adaptation by communities with limited means can be successful, using a combination of creativity, low-level construction techniques and some nature-based solutions (Jamero and others, 2017, 2018; Narayan and others, 2020).

One of the largest sources of uncertainty in monitoring, modelling and managing such low-lying islands is the limited availability of accurate high-resolution bathymetric and topography data (Pacheco and others, 2015)

with which to examine changes in coastal morphology over a larger spatial scale and at higher temporal frequency (Hamylton 2017; Vitousek and others, 2023). Satellite remote sensing, airborne light detection and ranging, and drone photogrammetry should be employed to obtain high-resolution bathymetric and topographic data, assess vegetation cover and analyse recharge and evapotranspiration on atoll islands (Andréfouët and Paul, 2023; Hamylton and others, 2020; Casella and others, 2017; Collin and others, 2018).

More attention has recently been focused on the resilience of atoll freshwater lenses to natural and demographic changes (Ketabchi and others, 2016). Notwithstanding the resource-intensive nature of hydrogeological investigations of atoll islands, there are a few long-established monitoring networks, such as those on Bonriki in Kiribati and the Cocos (Keeling) Islands. More high-quality investigations that encompass the full range of island sizes and environmental conditions are needed for the purposes of improving groundwater management and mitigation strategies for individual atoll islands (Werner and others, 2017; Sengupta and others, 2022). Even in well-studied atoll islands, scientists' understanding of the flow paths within the lens and mixing zone is surprisingly poor. In addition, a better understanding of the effects of tides in karstified island aquifers is needed, not least to reconcile discrepancies between mixing zones simulated using numerical models and those measured in the field (Martin and others, 2012; Ghassemi and others, 2000; Collignon, 2019). Groundwater resources on atoll islands are particularly vulnerable due to a combination of high-permeability soils and a thin vadose zone, but relatively little attention has been paid to biological and chemical contamination aside from aquifer salinization.

Numerical models can be used to simulate a wide range of physical, chemical and biological processes, develop a quantitative understanding of the interactions between different processes and predict responses to changes in environmental conditions and management practices. Two challenges common to computer simulations of any system are difficulties in model parameterization and a paucity of field data for validation (Splinter and Coco, 2021; Twomey and others, 2024). Moreover, the quantification of model uncertainty requires a suite of simulations to be run (Liu and others, 2022; Herrera and others, 2022). The potential use of the output as training data sets for machine learning algorithms (Reichstein and others, 2019; Papacharalampous and Tyralis, 2022) could be a powerful tool with which to address these challenges. It is critical to match modelling methods to project objectives, budget and available data. Relatively simple algebraic models can be rapid to implement. For example, Bailey and others (2021, 2022) and Sengupta and others (2021) calculate the future groundwater resources of 91 atoll islands in the Federated States of Micronesia from mean annual recharge, island width, Holocene thickness and hydraulic conductivity. As a final point, it should be noted that, although quantitative models are essential to describe risks and reduce uncertainty in resource management and climate change response projects, conceptual models may suffice for project managers to make informed decisions (Larsen and others, 2016; Twomey and others, 2024).

Restoration, conservation, mitigation and adaptation

The health of active coral reefs along atoll rims is one of the key properties that may mitigate the adverse effects of sea-level rise and increased tempestuousness. Reef crests act as natural breakwaters and dissipate incoming wave energy through wave breaking and bottom friction (Carlot and others, 2023; Huang and others, 2024), providing the ecosystem service of coastal protection. Rates of sea-level rise exceeding those of coral growth and reef crest accretion have a negative effect on the wave dissipation exerted by coral reefs (Baldock and others, 2014; Quartaet and others, 2015; Toth and others, 2023). Rising sea levels may also increase seawater circulation across the reef, moderating diurnal temperature extremes (and thus coral bleaching), as well as affecting lagoon flushing times, calcification rates and many other physically linked biological processes that affect the health and resilience of coral reef communities and those within the lagoon (Gruber and others, 2019; Lowe and others, 2016).

Many conservation measures have been proposed for the protection of atolls, ranging from passive to active initiatives. Active coral restoration projects have been developed around the world, but have so far failed to restore species or ecosystem functioning at a relevant scale. This is largely because the restoration performed is often undone by bleaching episodes associated with heatwaves and global warming (Hughes and Grumbine, 2023). This has caused some Governments to refrain from funding any further active restoration practices. It should be noted, however, that creating MPAs and neutralizing local-scale impacts (such as pollution, unregulated fisheries and tourism) have occasionally proved

effective in reducing global-scale impacts (Graham and others, 2008). Nevertheless, MPAs must be adequately designed, anticipating local oceanographic and biological factors, such as larval and other types of connectivity, which is critical for sustaining genetic and species diversity on atolls, which are often remote.

As with all coastal communities, the adoption of hazard mitigation and adaptation strategies by atoll nations is critically contingent on the communication of impacts to policymakers and users. Communities are more receptive to such messaging when sea level and climate metrics are explained in terms of local-scale societal impacts, such as the risk to hospitals, airports and similar facilities posed by both more frequent and rarer extreme sea-level events (Rasmussen and others, 2022). The survival of atoll nations, with the exception of urbanized atolls, depends on the development of cross-disciplinary collaboration to protect and restore exchanges of sediment, water and nutrients between atoll islands, lagoons and coral reefs. This does not apply to urbanized and densely populated atolls because several engineering solutions are available (Yamamoto and Esteban, 2017).

In this context, given the ecological uniqueness and vulnerability of atoll ecosystems, conservation measures must be tailored to their specific needs. Such measures include: (a) reducing CO_2 emissions to halt global warming and ocean acidification; (b) establishing and enforcing MPAs to limit local stressors; (c) implementing sustainable use programmes; (d) engaging local communities in conservation through education, awareness and sustainable livelihoods; and (e) supporting research and long-term monitoring programmes to address knowledge gaps and evaluate conservation efforts.



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Subchapter 5D
Tropical and subtropical coral reefs

Key points

- Global declines in coral cover persist, owing to increasing ocean temperatures associated with climate change, continued coastal development, pollution, sedimentation, diseases and the destruction and overextraction of marine resources (through fishing and coral harvesting). These stressors have an impact on coral biodiversity, reef-associated fauna and the architectural complexity of reef frameworks, compromising the food security and livelihoods of the millions of people who depend on these ecosystems (virtually certain, well established).
- The frequency and severity of disturbances caused by heatwaves, disease outbreaks and tropical storms have increased (virtually certain, established but incomplete), curtailing the recovery time between such disturbances. This pattern is projected to continue on its current trajectory (at best) or accelerate (very likely).
- The ecosystem services provided by coral reefs are substantial, not only in terms of biodiversity, but also in terms of direct economic benefits (including coastal protection, livelihoods for millions and nurseries for commercial species), as well as less tangible benefits, such as cultural and aesthetic (intrinsic) value (virtually certain, well established).
- Conservation, restoration and regeneration efforts are under way on a global scale, but few initiatives are implemented on a long-term, sustainable basis, with socioeconomic considerations, such as livelihoods, taken into account (virtually certain, well established). A wide range of approaches and tools is being developed, many of which are designed to mitigate or halt reef declines. These are often restricted to local reef-wide projects, however, and the potential for upscaling is sometimes criticized (unresolved). Documented results are also almost always undermined by a clear disconnect between these and other policy decisions, such as the extraction and burning of fossil fuels and coastal development (likely). Regardless of scalability concerns, all programmes need to be embedded within a broader evidence-based conservation framework.
- Global efforts are required to facilitate reef ecosystem survival and continued function by reducing emissions and ongoing climate change (virtually certain, established but incomplete). The reefs of today will not be the reefs of tomorrow (virtually certain) and shifting baselines need to be considered when setting objectives with respect to conservation, restoration and regeneration (virtually certain, established but incomplete).

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1. Introduction

Coral reefs stand as one of the planet's most valuable natural assets, supporting approximately 25% of marine life and providing some level of support to approximately 1 billion people across more than 100 nations (Fisher and others, 2015; Sing Wong and others, 2022). For example, 70% of the protein intake among Pacific Islanders comes from reef-associated fisheries (Charlton and others, 2016), and reefs are heralded as the medicine chests of the twenty-first century (Blockley and others, 2017).

The value of goods and services provided by coral reefs is estimated at $2.7 trillion. This includes $7 billion per year in food security and livelihoods, $6 billion in shoreline protection and $36 billion in services to the global tourism industry (Souter and others, 2021).

2. Environmental changes since the second *World Ocean Assessment*

Changes in overall status

Global coral reef conditions have continued to deteriorate since the second *World Ocean Assessment*, with multiple compounding threats intensifying across all major reef systems (see figure I). Recent evidence demonstrates both an accelerating decline in, and increasingly complex challenges to, reef survival (Gutierrez and others, 2024).

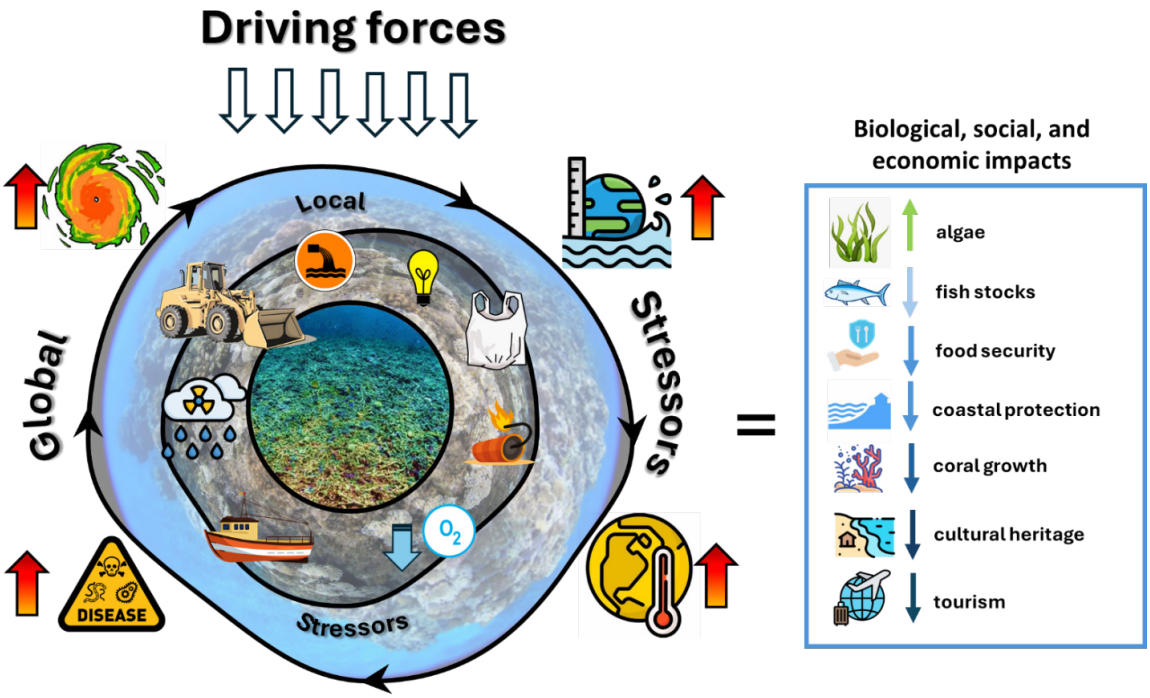
Marine heatwaves between 2018 and 2025 have triggered widespread coral mortality through recurring global-scale coral bleaching events (Eakin and others, 2019; Moriarty and others, 2023). Due to local stressors, there remains uncertainty regarding coral recovery rates (Donovan and others, 2021; Brown and others, 2023; Walker and others, 2024). The scientific evidence demonstrates (with high levels of certainty) that the global temperature rise should be constrained to no more than 1.5°C to 2°C above pre-industrial levels in order to avoid the most serious consequences of climate change for coral reefs (Lenton and others, 2023). It has been proposed by some that this threshold represents a critical biological limit, or "tipping point", beyond which reef ecosystems face potentially irreversible consequences. Others argue, however, that the term "tipping point" can sometimes cause confusion and even distract from the urgent climate action that is needed (Kopp and others, 2025).

Regardless of the terminology, nearly all scientists agree that reefs will be affected by a temperature rise of as little as 1.0°C above pre-industrial levels, and coral-dominated communities (as we know them today) will essentially disappear under Representative Concentration Pathway (RCP) 6.0 and RCP 8.5 as defined in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Even under less severe warming scenarios (RCP 4.5) the outlook looks dire, with sharp declines in reef cover occurring; however, some scientists remain optimistic that recovery is possible, with sufficient genetic variability persisting (McManus and others, 2021) (established, but incomplete). Indeed, limiting warming to 2°C or less may allow coral reefs to survive until 2100 without drastic shifts in community composition (Logan and others, 2021).

It is, however, rather alarming to note that more current scientific assessments are understood to indicate that even maintaining temperature rises below 1.5°C presents substantial risks to reef ecosystem survival (established, but incomplete) (Dixon and others, 2022). There is already evidence that temperature rises in some regions have approached or even crossed the upper end of this range and that warming above 1.5°C on a global scale is expected by as early as 2034. Ocean warming above 2.7°C is further expected around 2100 (likely, well established). If realized, this exceeds even the optimistic thermal safety margins for coral survival.

Major regional shifts in reef composition and reef-associated fish species are already being documented (Edmunds and others, 2014; Ceccarelli and others, 2024). This is alongside decreased habitat complexity (Edgar and others, 2023), increasing impacts from nutrient pollution (Nalley and others, 2023) and reduced recovery periods between stress events (Emslie and others, 2024). Hypoxic conditions are present on 84% of surveyed reefs, with 13% experiencing severe oxygen depletion (Pezner and others, 2023). Disease prevalence has reached unprecedented levels (Burke and others, 2023), and reefs are being exposed to intensifying ocean acidification (IPCC, 2019), shifting salinity patterns and increasing freshwater flood impacts (Röthig and others, 2023) (see figure I).

Figure I
Factors contributing to changes observed in coral reefs



Source: Prepared by the writing team.

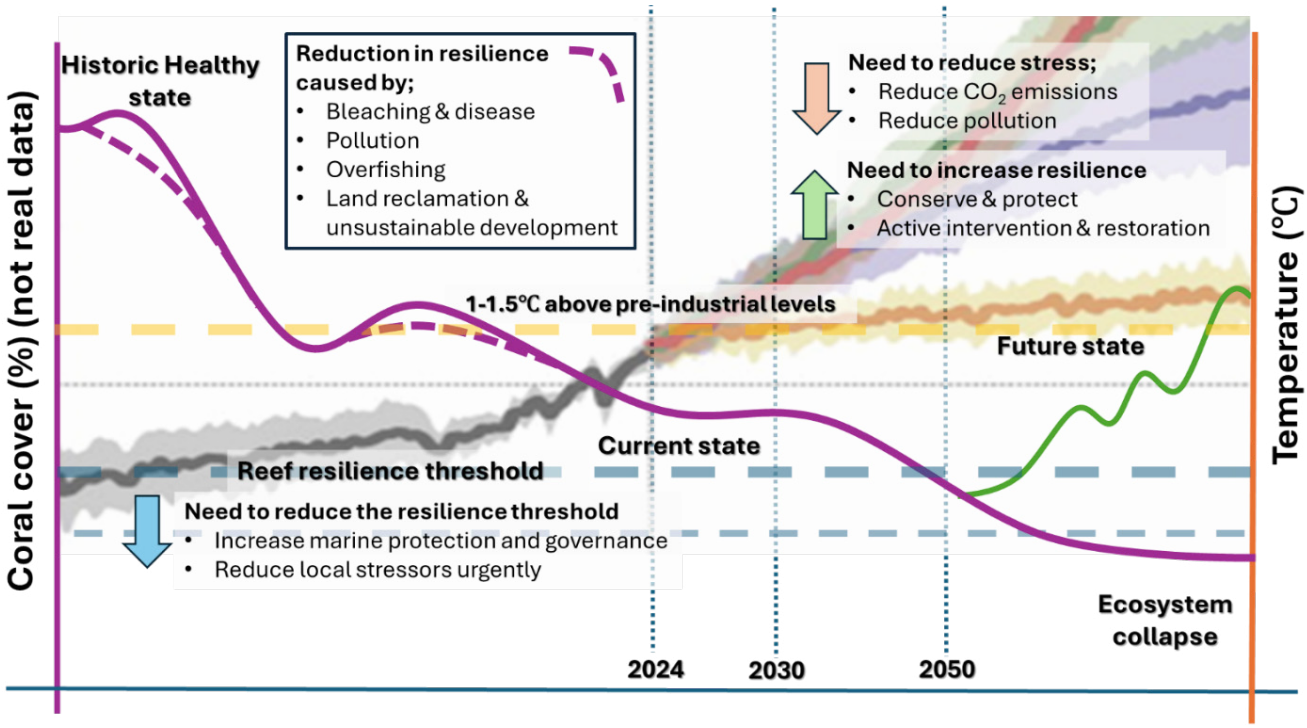
Note: This infographic highlights the main factors contributing to the changes observed to coral reefs; it shows drivers, cumulative global and adaptive local stressors, the current state of reefs, the resulting impacts and responses. Driving forces include ongoing human activities, such as rapid economic growth, the linear economy, overconsumption, overpopulation, corruption, overexploitation of reef resources for short-term economic gain and insufficient investment in sustainable practices and conservation efforts. Stressors act at the global (outer circle) and local (inner circle) scales, and in many cases are cumulative or additive. Local stressors are region- and site-specific and occur in addition to global stressors, ultimately affecting how coral reefs respond to bleaching and disease. Reefs, in general, are experiencing decreased coral cover, habitat degradation, reduced biodiversity, disrupted food webs and the loss of foundation species and ecological functioning, resulting in several biological, social and economic impacts. To save these ecosystems, urgent action must be taken to reduce the carbon footprint, transition to a circular economy and increase political support for conservation. It should be noted that the focus is on cumulative impacts; the scale of each stressor has not been indicated.

The notion of subtropical and temperate reef refuges is being refuted and earlier hopes for natural adaptation through poleward expansion or deep refugia have proved overly optimistic. Indeed, temperate coral reefs experience lower winter temperatures than those in tropical locations, affecting the diversity of the community of fish species that can become established (Booth, 2020); coral bleaching and subsequent mortality events are more frequent and more severe in temperate locations (Lachs and others, 2021); and such reefs exhibit high coral endemicity (Mizerek and others, 2021) and high environmental stochasticity (Beger and others, 2014). Furthermore, any apparent gains that do occur at subtropical locations are almost certainly unlikely to offset losses seen in the tropics (Adam and others, 2021). Even previously identified "bright spots" (where corals survive present-day heatwaves) (Cinner and others, 2016; Fox and others, 2021; Brown and others, 2023) have shown vulnerability to extreme events, as demonstrated in the South Atlantic. Once considered a refuge from bleaching events, this region suffered 80–90% mortality of dominant reef-building corals during a 50-day marine heatwave in 2019 (Duarte and others, 2020).

Despite isolated cases of recovery or even coral cover stability (Chan and others, 2023), the overall global trajectory indicates compromised reef resilience (see figure II). Indeed, the increasing frequency of disturbances leaves insufficient time for recovery between events (Emslie and others, 2024). This results in demographic shifts, the homogenization of reef-associated communities, compromised resilience of the reef ecosystem at large, simplification in habitat structure and decreased structural complexity (Richardson and others, 2018; Magel and others, 2019; Sommer and others, 2024).

Figure II

Compromised reef resilience and decadal decline of coral cover with an even bleaker future outlook



Source: Prepared by the writing team.

Note: The overall trajectory of global coral reefs indicates compromised resilience and a decline in coral cover (purple line). Coral cover lines are not based on real data and represent a generalized trend of what is occurring on a global scale. A further reduction in reef resilience is highlighted by the dashed lines, indicating more rapid decline in some areas than in others. There is an unarguable need to reduce the stress faced by reefs (namely by reducing or reversing climate change (orange arrow)), while simultaneously attempting to increase resilience (green arrow). There are two key approaches to increasing resilience: reducing the reef resilience threshold (blue arrow and blue dashed lines) and increasing reef resilience (green arrow). Average increases in sea-surface temperature (°C) and possible scenarios of future change are depicted in the graph. The data are derived from the sixth assessment report of IPCC. The critical threshold of 1–1.5°C should not be breached if functional coral reef ecosystems are to remain. There is a very real possibility that ecosystem collapse may occur if significant action is not undertaken immediately. Reducing all stressors, where possible, and improving general water quality (orange arrow) will likely result in many reefs around the world being restored or regenerated to a functional state (green line). Indeed, corals remain remarkably resilient and able to adapt to a degree of climate change.

3. Region-specific changes

Mediterranean

The Mediterranean presents an alarming and unique case of accelerated warming, with rates three times the global average (Dayan and others, 2023; Copernicus, 2024). The marine heatwave of 2022 was particularly severe, with surface temperatures reaching 31°C and thermal anomalies extending to unprecedented depths, exceeding 27°C at 20 m (Castellanos-Galindo and others, 2020; Ozer and others, 2022). These episodes of intense warming have triggered mass mortality events among sessile benthic species, affecting octocoral populations in particular (Capdevila and others, 2024).

South Atlantic Ocean and wider Caribbean

The Caribbean region represents one of the most dramatic examples of long-term reef decline, with coral cover having reduced by more than 80% since systematic monitoring began in the 1970s (Gardner and others, 2003; Schutte and others, 2010; Precht and others, 2020). Although this value has been queried in a recent report produced by the Global Coral Reef Monitoring Network (Souter and others, 2021), the situation in this region has certainly been exacerbated by the 2023 thermal stress event, which began months earlier and caused 2–3 times the heat stress of previous events (Hoegh-Guldberg and others, 2023). In Little Cayman, for example, approximately 80% of corals either bleached or showed signs

of mortality during this period and 54% were found dead during the final survey (Doherty and others, 2025). This catastrophic loss in coral is despite approximately 57% of the coastal environment being classified as no-take marine protected areas (MPAs).

Of particular concern in the Caribbean is the shift in coral community composition from critical framework-building genera, such as *Acropora* and *Orbicella* (Toth and others, 2023), to more stress-tolerant species, such as *Agaricia, Porites* and *Siderastrea* (Aronson and others, 2002; Green and others, 2008; Toth and others, 2019).

The emergence in 2014 of stony coral tissue loss disease has further affected reefs in this region (Precht and others, 2016; Alvarez-Filip and others, 2022). The disease is persistent and has caused local extinctions of some species (Neely and others, 2021). While treatment efforts using antibiotics and probiotics have shown some success (Neely and others, 2020; Pitts and others, 2025), reinfection remains a significant challenge (Kozachuk, 2024; Zummo, 2024).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf, Strait of Malacca and South China Sea

Recent bleaching events have shown marked variation in impact across subregions (Souter and others, 2021). For example, the reefs in the Mozambique Channel and south-western Madagascar show surprising resilience, whereas those in Kenya, Seychelles and the United Republic of Tanzania have experienced severe degradation (Obura and others, 2022).

The reefs in the Persian Gulf and the Red Sea were historically heralded for their thermal tolerance (Osman and others, 2018); however, these are now also in decline (Anton and others, 2020). Coral cover in the Persian Gulf dropped from 27% in 2019 to 12% in 2022 (Burt, 2024), while some reefs in the central and southern Red Sea have declined by up to 45% (Anton and others, 2020). In the Red Sea, coral community responses do appear to be region-specific, with communities in the southern and central regions more commonly affected by mass bleaching events than those in the north (Gonzalez and others, 2024). Coral cover has declined from over 40% (2014) to under 5% (2018) in such locations as Al Lith, Farasan Banks and Farasan Islands (Gonzalez and others, 2024). Coral cover in the eastern Arabian Sea also dropped significantly, from 45% in 2014 to 20% in 2019 (De and others, 2023).

Pacific Ocean

Studies appear contradictory regarding coral cover in this region. For example, the authors of some studies present reefs as having stable trends in cover over the past decade (Chan and others, 2023), whereas those of other studies report accelerating loss beyond previous projections (Souter and others, 2021). There is evidence to suggest that the consequential effects of climate warming are often delayed in certain regions, primarily as a result of such factors as large interdecadal variations in the coral triangle area (Zinke and others, 2018).

In the East Asia region, more coral on average was reported in 2019 than in 1983 (Souter and others, 2021). To take the example of Malaysia, however, 50.7% of corals bleached in 2024, and this later resulted in 34.1% dying – although again regional variation was reported, with the north-eastern parts of the peninsula being more affected (Szereday and others, 2025).

The Great Barrier Reef also showed a slight increase in reported regional hard coral cover in the early part of 2024 compared with the levels reported in 2022 and 2023 (Australian Institute of Marine Science (AIMS), 2024). This finding preceded the bleaching event of 2024–2025, however, during which temperature anomalies in the Great Barrier Reef exceeded the 95th percentile of pre-1900 baseline measurements (Henley and others, 2024). In 2024 and 2025, the southern Great Barrier Reef saw severe and widespread bleaching to levels not previously recorded (Byrne and others, 2025). At One Tree Reef, for example, 80% of monitored coral colonies bleached and 53% died shortly afterwards. Colony collapse occurred in 95% of the *Acroporas* assessed (Byrne and others, 2025). The protected status and offshore location of One Tree Reef did not protect the corals from heat stress, bleaching and mortality.

It is concerning that evidence of local extinctions of coral and population depletions across multiple species has already begun to appear in many surveys with similar small, region-wide spatial scales (Richards and others, 2021). This indicates that although general trends in coral cover may be stable (in part), a fundamental shift in community composition is occurring (Chan and others, 2024).

For more nearshore areas, cumulative pressures (such as sediment and nutrient run-off) have been highlighted as a particular concern in the region. Indeed, the reduction of pollutant loads has been slow due to only modest improvements in land management to date (Queensland government, 2020).

4. Knowledge gaps, challenges and capacity changes

Although advances have been made to address the knowledge gaps identified in the second *World Ocean Assessment*, there are still key points that present significant challenges. These include understanding barriers to political will, strengthening governance and increasing recognition of the socioeconomic value of habitats with respect to, for example, local nutrition and food security. It is also important to focus on understanding how to enhance reef resilience and monitoring reef status and drivers of change, ensuring that cumulative global and local stressors, their resulting impact and responses are taken into account (see table).

The future of coral reef ecosystems hinges on the ability to align global emissions policies with local protection efforts. The ramifications of not addressing these concerns will extend far beyond coastal communities, affecting food security, economic stability and social justice worldwide.

As climate impacts on reefs intensify, there is increased understanding of the benefits (and limitations) of resilience-based tools and adaptive interventions that can be applied in coral conservation and regeneration efforts (Mcleod and others, 2019; Shaver and others, 2022).

Knowledge of the sustainable management of coral reef fisheries is also improving (Zamborain-Mason and others, 2023). Indeed, the authors of the latter study conclude that most reef fish stocks open to extraction are currently compromised, especially in the context of aiming for maximum long-term production. Reef fish are critically important for food and nutrition security and the livelihoods of millions of the most vulnerable people in the world. In this context, additional efforts to achieve sustainable management and governance of these fisheries (through a multidimensional lens, for example) are not only desirable, but imperative (Basurto and others, 2025). It is also widely agreed that such management systems need to be suited to the small-scale nature of most coral reef fisheries, which tend to be located in regions of the world with limited technical and institutional capacities (Cinner and others, 2020). Catch, poverty eradication, shared governance, advancing gender equality and nutrient supply all need to be considered. This can be done by ensuring that: (a) small-scale fisheries are built into trade statistics; (b) there is fair distribution of catch benefits, with fishers' tenure rights secured; and (c) aquatic foods are affordable and accessible to all.

Major capacity gaps that remain in this space include insufficient policy support, a lack of scalable restoration methodologies and limited access to and on-the-ground training on the most advanced and promising monitoring technologies (Madin and others, 2019). Reef restoration practices that are self-sustaining (regarding their finances and funding) should be highlighted as examples of good practice if they exist already. Regular and consistent monitoring should be integrated into all management strategies and practices (Voolstra and others, 2023), and there needs to be a general improvement in coordination for capacity development (Obura and others, 2019).

It must be acknowledged that future coral reefs will differ from historical baselines (see figure II). Management and conservation initiatives should explore best practices that enable a transition to the best possible new state and ensure a level of support for biodiversity and the livelihoods and dependence of coastal economics and people as reef ranges shift. Critical assessment of any outcomes and impacts is essential and should now be mandatory. The protection of high-value genotypes in biobanks is likely to become a priority, with the aim of conserving genetic diversity and even the survival of species. Clear and open efforts must be made to differentiate between the environmental costs of destroying coral reefs for developmental purposes, which benefits a few, from the economic benefits of effective reef protection, which benefits everyone.

While advances have been made to address the knowledge gaps reported in the second *World Ocean Assessment* (including gaps in relation to the responses of reef communities to climate change, the socioeconomic value of coral reefs and the distribution and ecology of mesophotic coral reefs), key gaps remain pertaining to the enhancement of reef resilience in the face of climate change, strengthening reef governance and management, and recognizing the socioeconomic value of coral reefs. Suggested action points for each of these themes are set out in the table.

Table
Knowledge gaps and suggested action points

Theme 1: enhancing reef resilience in the face of climate change
Establish standardized ecological and socioeconomic international or national coral reef monitoring and restoration networks and support existing global programmes. Track longer-term trends and stress impacts, such as climate impacts, including storms and anoxic events, and disease and invasive species outbreaks (see sect. 4, chap. 6), and map newly discovered reefs and sentinel coral colonies.
Identify climate-resistant coral species and genotypes. Explore and, where possible, scale up intervention strategies, such as cryopreservation, biobanking, assisted evolution and assisted gene flow.
Develop a centralized database integrating diverse reef-related data (including photogrammetry, acoustics, diversity assessments and environmental parameters). Create "digital twins" to improve decision-making.
Launch a comprehensive marine biodiversity assessment programme involving integrated taxonomic and molecular research to consider cryptic taxa and explore the risk of silent extinctions of species and loss of genetic diversity.
Theme 2: strengthening reef governance and management
Implement a framework for active reef interventions, ensuring local appropriateness and effectiveness. Participatory methods that include Indigenous Peoples should be strongly encouraged.
Increase Member States' capacity to collect, analyse and use data to inform fisheries management decisions and policies aimed at maximizing food production and livelihoods while maintaining the structure and functioning of coral reef ecosystems.
Develop and execute a reef adaptation strategy linked to sustainable ocean plans addressing rapidly changing environmental conditions.
Establish a coral reef community empowerment programme to increase local capacity for the management of reef fisheries. Listen to stakeholders and include them in decision-making.
Create national standards for reef-related nature-based solutions aligning with international best practice.
Increase the number of scientific studies on local, regional and global causation, relating transdisciplinary indicators of anthropogenic impacts to the health state of coral reef organisms and ecosystem integrity worldwide.
Improve the design and enforcement of existing MPAs. Banning nets and spearguns on reefs, for example, would increase global reef fish stocks by approximately 10.5% – essentially matching all conservation efforts to date (Caldwell and others, 2024).
Implement policies to minimize land-based sources of pollution. Targeted environmental impact assessments should be undertaken to identify key point-sources of localized pollution. Turn lights off (especially around the coral spawning window), improve waste management and establish buffer zones along coastlines to reduce sediment, nutrient and contaminant inputs.
Theme 3: recognizing the socioeconomic value of coral reefs
Commission a comprehensive economic valuation of national coral reef ecosystems. Differentiate between the environmental costs of destroying coral reefs for development and the economic benefits of effective protection.
Integrate reef value assessments into national infrastructure and development planning. Citizen science helps to involve communities in efforts to improve management effectiveness.
Explore innovative pathways to protection, intervention or restoration, such as reef insurance.[1]

Source: Prepared by the writing team.

In conclusion, if the planet's carbon footprint is not significantly lowered, coral reefs of the kind seen today will almost certainly cease to exist, and the reefs of the future will be very different ecosystems, likely less complex, harbouring lower biodiversity and offering reduced ecosystem services.

This unfolding crisis represents both an ecological and a human rights issue (Sweet and others, 2021; Camp and others, 2024; see also subsect. 5B, chap. 2). It disproportionately affects vulnerable populations, including those in communities with lower socioeconomic status, poor coastal States, States with weak governance and high corruption, and small island nations or large ocean States.

The occurrence of the fourth global mass coral bleaching event in 2024–2025 affected over 77% of the world's reefs and marks another stark milestone in reef decline (Reimer and others, 2024). Furthermore, the increasing

[1] See www.abterrace.com.au/item/introducing-coral-reef-insurance.

frequency and severity of such stress events are compromising coral resilience by reducing recovery windows between disturbances (Emslie and others, 2024). Immediate climate action must include emission reductions and integration with economic policy.

Local management requires addressing immediate threats through policy, while ensuring effective fisheries management and marine conservation, building local support with stakeholders and fostering marine spatial planning.

MPAs cover 8% of the oceans; however, it has been reported that approximately a quarter of the largest MPAs lack effective implementation and policies with respect to a third appear incompatible with conservation goals (Pike and others, 2024). These findings have been attributed to the fact that many MPAs are reported as lacking regulations or management, and some allow high-impact activities. Despite these challenges, when properly designed and managed, protected areas are well documented to support upward of 10% higher fish biomass, improved ecosystem resilience and enhanced recovery potential (Benedetti-Cecchi and others, 2024; Caldwell and others, 2024).


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It should also be recognized that there are some examples of effective enhancement of reef ecosystem-based adaptation (Bindoff and others, 2019). Indeed, some have even shown measurable effects on reducing climate risks (medium confidence; Bindoff and others, 2019). Nonetheless, current restoration practices have been criticized as costly endeavours and fundamentally remain a local intervention at best. Some have gone so far as to state that coral reefs need "evidence-based management not heroic interference" (Streit and others, 2024). Indeed, restorative practices will certainly not solve the global degradation of coral reefs due to anthropogenic climate change, and few would challenge that statement. It is important to note, however, that the cost of inaction, the cost of further degradation and the ultimate resulting loss of ecosystem services must also be weighed (Peixoto and others, 2022, 2024; Suggett and others, 2024).

The increasing acknowledgement of the ecosystem services offered by coral reefs (Reguero and others, 2021), along with an increased desire to use nature-based solutions to address the issues faced by humanity (Storlazzi and others, 2025), has resulted in the creation of large pre-disaster hazard mitigation funding pathways (ranging from tens of millions of dollars to billions of dollars) and post-disaster recovery funds, many of which are being channelled into reef restoration and preservation (Stovall and others, 2022). This is entirely justified, as the anticipated continued decline of reefs threatens not only marine biodiversity, but also the 1 billion people who depend on them.

The response to this crisis will determine not only the future of coral reefs, but also the well-being of human communities who depend on them for food, nutritional security and livelihoods (Food and Agriculture Organization of the United Nations (FAO), Duke University and WorldFish, 2023). Protecting, managing, conserving and restoring reefs should not be viewed as an altruistic quest; instead, it should be seen for what it is – a pragmatic goal to sustain human civilization and all life on Earth.

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Subchapter 5E
Cold-water corals and sponges

Key points

- Exploration of the oceans has revealed the nearly ubiquitous presence of cold-water coral gardens, reefs and sponge grounds on hard substrata throughout the world.
- There is increasing evidence of profound changes in the physical and chemical environment of the deep ocean, threatening cold-water corals and sponges (CWCS) habitats.
- Offshore industrial development continues to pose threats to CWCS habitats globally, with emerging threats from deep-sea mining and marine carbon dioxide (CO_2) removal.
- Additional CWCS are being discovered and protected, and are future targets for protections and the development of restoration strategies.
- Ecosystem services-based management is a new philosophy emerging from work in these areas, with a particular focus on the ability of CWCS habitats to sequester carbon on a large scale.

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1. Introduction

The present subchapter will focus on CWCS, the habitats they form and the services they provide in the deep sea (at depths of below 200 m). This includes many of the habitat-forming corals that create vulnerable marine ecosystems, including scleractinian stony corals, antipatharian black corals, octocorals and stylasterid lace corals, and habitat-forming sponges. The baseline state of CWCS has declined since the second *World Ocean Assessment*. Fishing in deep waters continues around the world, and oil and gas development is entering new areas and moving deeper in the ocean. Deep-sea mining and marine CO_2 removal have both entered the trial phase and have the potential to be stressors in the near future (Levin and others, 2023). In addition, climate change is a pervasive threat and the deep ocean absorbs a considerable amount of heat and CO_2.

Among the most significant recent academic advances is the publication of an edited volume in the Coral Reefs of the World series entitled *Cold-Water Coral Reefs of the World* (Cordes and Mienis, 2024). This includes descriptive summaries of CWCS ecosystems in various regions of the world, along with a summary chapter establishing a new global model of scleractinian coral habitat suitability, including the suitability of habitats for coral reef formation (see figure I). According to that analysis, cold-water coral reefs form in areas with especially high current speeds and dissolved oxygen availability, as compared with areas where corals are present but do not form large reef structures. Similar approaches have also been used to explore future suitable areas for habitat-forming sponges, highlighting how depth, temperature and dissolved oxygen are key drivers (Gregório and others, 2024).

Over the past few years, the Blake Plateau along the Atlantic coast of the United States of America has been completely mapped using multibeam sonar, which revealed over 30,000 km^2 of CWCS mounds, including a continuous area covering 26,000 km^2 (Sowers and others, 2024). This revealed new areas of cold-water coral reefs beneath the Gulf Stream that appeared to have some of the most variable oceanographic conditions observed, including temperature swings from 4°C to over 10°C in 24 hours, and among the highest nitrate concentrations recorded in the western Atlantic (Cordes and others, 2023). Studies have also highlighted how CWCS mounds grow into the prevalent directions of the current (Corbera and others, 2022), altering hydrodynamics to facilitate mound growth and sedimentation (Van der Kaaden and others, 2020). Paleoecological studies of cold-water coral mounds have revealed some of the key drivers of their persistence through time, demonstrating the importance of food supply and dissolved oxygen concentration (Raddatz and others, 2020a; Portilho-Ramos and others, 2022), which are also affected by large- and small-scale hydrodynamics.

On a finer scale, in the present day, the biomass distribution on CWCS reefs has been found to demonstrate metre-scale fauna clustering on the reef structure (de Clippele and others, 2021a). Sponges within CWCS reefs can act by recycling dissolved organic matter into particulate detritus, which can then be ingested by other CWCS fauna (Bart and others, 2021). This "sponge loop" contributes to the overall food availability of CWCS habitats and should be considered in future projections. The corals forming CWCS are well adapted to highly variable food delivery (Carrick and others, 2024) and the communities they support have evolved to optimize carbon and energy transfer through the food web (Maier and others, 2021, 2023). *Lophelia pertusa*, synonymized as *Desmophyllum pertusum*, was found to be well adapted to fluctuations in food supply through high capture capacities, resource flexibility, investment in tissue reserves and synchronizing activity to seasonal fluctuations in food availability (Gómes and others, 2022; Maier and others, 2023). Recently developed methods have been used to determine that the carbon turnover of cold-water coral reefs may be approximately three times higher than that of soft sediment areas at similar depths (de Clippele and others, 2021b). Biogeochemical metabolic flux models of how deep-sea sponges and their microbial communities transform different types of carbon and nitrogen shed light on how dissolved organic matter acts as a primary energy source for sponges (de Kluijver and others, 2021).

The threat of climate change to CWCS will vary by region and depth and will include changes in temperature, deoxygenation, ocean acidification and reduced food supply. Corals or sponges with narrower environmental ranges will be more at risk (Dijkstra and others, 2021), and the slow growth rate of these deep-sea organisms, coupled with limited dispersal capabilities in some cases, places them at particular risk (Cordes and Mienis, 2024; Gregório and others, 2024). The onset of ocean acidification is of particular concern to the dead exposed coral skeleton, leading to the dissolution of the aragonitic skeleton and

"coralporosis" (Hennige and others, 2020). This can lead to a loss of structural integrity (Wolfram and others, 2022) and the collapse of the coral framework (see figure II). The loss of the dead framework will act directly on the types of biodiversity within CWCS ecosystems as reef sessile suspension feeders cannot attach to strongly degraded reef framework and coral rubble (Maier and others, 2021, 2023). This will, in turn, affect nutrient recycling within the habitat and also change local hydrodynamics, which may affect food capture and the growth of remaining live coral (Corbera and others, 2022).

Restoration activities are increasing, leading to greater understanding of the associated techniques and challenges for both framework- and non-framework-forming coral species. This includes guides on techniques (Boch and others, 2020), reviews of the challenges to overcome with recommendations for future work (Liu and others, 2024; Montseny and others, 2021a; Bravo and others, 2023) and advice on how local communities and stakeholders can be integrated into restoration efforts (Montseny and others, 2021b). There is at present no overarching global scheme for the conservation and restoration of CWCS ecosystems, although they are generally considered vulnerable marine ecosystems in the European parlance and managed as essential fish habitat in the United States.

2. Environmental changes since the second *World Ocean Assessment*

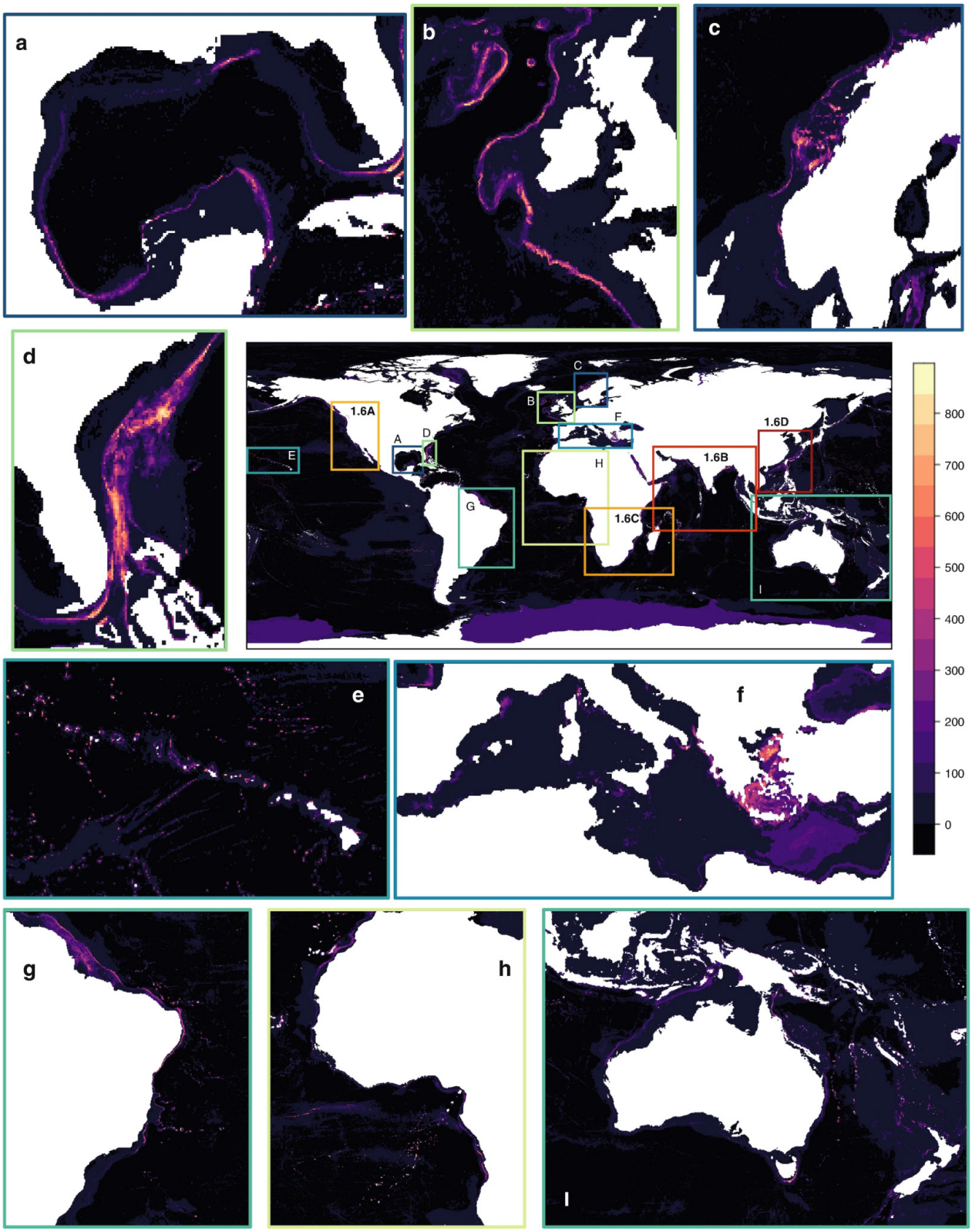
While advances have been made in understanding of environmental changes since the second *World Ocean Assessment*, a lack of long-term baseline data at CWCS sites still limits understanding of long-term change. It is clear that the deep sea is warming (well established), but it is difficult to say how quickly (inconclusive). There is evidence of more frequent "marine heatwaves" (well established) but less information on how deep they penetrate and how frequently they reach the deep seafloor (unresolved). The risks and potential impacts of typical offshore industrial activities (Cordes and others, 2016) and catastrophic incidents, such as the Deepwater Horizon disaster, are well established (Schwing and others, 2020). This has not curtailed offshore drilling, however. Similarly, for fisheries, the impacts of bottom trawling on benthic communities are understood (well established), including as regards CWCS (Du Preez and others, 2020; Williams and others, 2020).

To understand the threat of climate change to CWCS ecosystems, there is a need to combine both experimental and in situ studies and observations. This combination has been used in environmental niche modelling to predict changes in habitat suitability for key cold-water coral species, with declines of between 28% and 100% predicted by the end of the century in high-emission scenarios (established but incomplete). The largest reductions were for the framework-forming *Desmophyllum pertusum* and the octocoral *Paragorgia arborea* (Morato and others, 2020). According to predicted distribution models, the trend for sponges will be similar to that of cold-water corals: habitats may shift (and expand, in some cases, with the area suitable for the glass sponge *Vazella pourtalesii* on the Scotian Shelf increasing by up to four times its current size), but there will be an overall trend of reduced suitability in areas where these habitats are currently found (Beazley and others, 2021). An added complication is the fact that the impacts of climate change will take effect at the same time as those of established human stressors (such as fishing) and emerging human stressors (such as mining and marine CO_2 removal). For example, bottom trawling at depths in excess of 800 m was banned in Europe in 2016, but these activities continue in many other areas of the world.

There is a lack of data on how long it may take for cold-water coral reefs to be affected by climate change. Paleo-records of key framework-forming species are of great benefit in this regard (Portilho-Ramos, 2022), as observation of impacts in situ is limited by regional capacity for monitoring and repeated observation over potentially decadal timescales. Paleo-records can also be used to identify key drivers of past impacts (e.g. food supply through local hydrodynamics) and provide insights into how present-day reefs can survive in suboptimal conditions (e.g. low oxygen), such as CWCS off the Mauritanian Margin (Portilho-Ramos, 2022). There have been very few studies of the effects of climate change on coral gardens (consisting of octocoral sea fans, antipatharian black corals, stylasterid hydrocorals and others) and sponge beds (unresolved).

Figure I

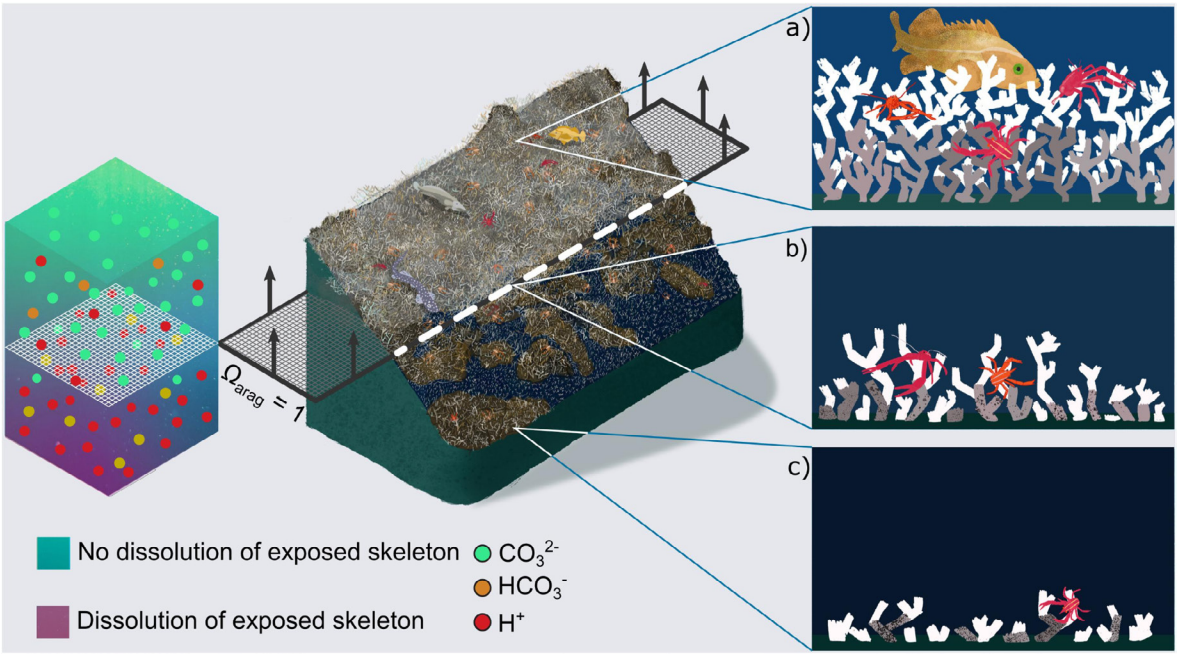
Map of ensemble-weighted mean habitat suitability index scores for cold-water corals and sponge reefs and reef-forming taxa known to occur in the regions of the world



Source: Reproduced from Cordes and others, 2023.

Note: CWCS reef regions are shown for the following locations: (a) Gulf of Mexico; (b) United Kingdom of Great Britain and Northern Ireland, and Ireland; (c) Norway; (d) south-eastern United States; (e) Hawaii; (f) Mediterranean; (g) eastern Brazil; (h) West Africa; and (i) south-western Pacific. Habitat suitability index scores for reef development are shown on the colour ramp, from highly unsuitable (0, black) to highly suitable (1,000, yellow). Major land masses are shown in white.

Figure II
Cold-water coral habitat loss in a future ocean



Source: Hennige and others, 2020.

Note: The central image shows *Desmophyllum pertusum* reefs under present-day conditions (top) and their projected habitat loss in a future ocean once the aragonite saturation horizon (dashed layer at ΩArag = 1) rises above them. A qualitative chemistry scale bar indicates dissolution of exposed aragonite beneath the horizon driven by increased [H^+] and decreased [CO_3^{2-}] ions. Arrows on the dashed layer indicate the projected direction of movement of the aragonite saturation horizon driven by ocean acidification. Panels on the right zoom into areas of present-day and future reefs related to the position of the aragonite saturation horizon. In (a), a healthy reef is shown with a substantial live (white) and dead (grey) coral framework. In (b), porosity has started to appear in the dead, exposed skeletal framework, leading to crumbling. In (c), the exposed skeletal framework exhibits large porosity and is unable to support a complex three-dimensional habitat, although high abundances of live coral can still exist.

3. Region-specific changes

Arctic Ocean

The number of studies of CWCS, which are pan-Arctic ecosystems, has increased since 2018 with the aim of identifying key biodiversity hotspots of CWCS across several areas, including the continental shelves of Greenland and Norway, as well as fjords around Svalbard (Puerta and others, 2020). The Davis Strait hosts important sponge grounds and soft coral fields (Maier and others, 2024), but the inaccessibility of some areas (due to such factors as sea ice) means that these studies are often based on singular or episodic observations. The Karasik seamount expedition revealed that some deep-sea sponges, such as *Geodia parva* and *Stelletta rhaphidiophora*, can move across the seafloor (Morganti and others, 2022).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

Understanding of how overturning circulations provide surface food supply to reefs around the North and Eastern Atlantic has improved (Juva and others, 2020; de Froe and others, 2022), including understanding of historical patterns in the Baltic Sea (Raddatz and others, 2020a). In particular, it is clear that current CWCS reefs may be at risk due to water column stratification associated with climate change. Quantification of water mass dynamics also supports better understanding of larval flow between CWCS areas (Schulz and others, 2020) and the identification of unique sponge fauna in the Mediterranean (Santín and others, 2021). Since 2019, there has been some progress in the protection of cold-water coral habitat in such areas as Eastern Canyons Marine Refuge in Canada, the

West of Scotland marine protected area (MPA) and the Tristan da Cunha MPA in the Southern Atlantic.

South Atlantic Ocean and wider Caribbean

Despite the dire need to curb fossil fuel use, offshore drilling continues to expand around the world, moving into frontier areas of the deep ocean in the southern Caribbean, West Africa and South America. Detailed mapping of the mounds off Brazil (Raddatz and others, 2020b) and Mauritania has revealed a wider distribution and greater abundance of CWCS than previously thought. The systems off West Africa seem to be surviving, and in some cases thriving in waters with extremely low oxygen, in contrast to findings elsewhere (Hebbeln and others, 2019). New taxonomic and coral distribution work in South Africa (Filander and others, 2021, 2024) is strengthening the knowledge base with the discovery of many coral gardens, and new offshore MPAs have improved CWCS habitat protection, with eco-certification initiatives for fisheries supporting further improvements in the management of CWCS and vulnerable marine ecosystems (Sink and others, 2023).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Taxonomic knowledge of CWCS is advancing in Africa (Filander and others, 2021, 2024; Hanafi-Portier and others, 2024; Samaai and others, 2020) and museum records are being used to examine diversity patterns in the Indian and Atlantic Oceans (Filander and others, 2024). There has been little progress in mapping cold-water coral habitats along the African continental margin, but new expeditions in the Red Sea have increased cold-water coral species and reef discovery and baseline data in that region (Qurban and others, 2020; Chimienti and others, 2022; Maggioni and others, 2022). Cold-water coral protection is lacking along most of the African margin for both the Indian Ocean and the Atlantic Ocean, and there has been limited or no progress in protecting cold-water coral habitats in the high seas of that region. Offshore drilling continues to expand in the Bay of Bengal, Indonesia and elsewhere and continues to threaten CWCS ecosystems before they are even discovered.

North Pacific Ocean

In the north-western Hawaiian Islands, gradients in fishery pressure were related to the size and density of corals on seamounts (Baco and others, 2023). There had been some recovery of corals on seamounts where fishing had occurred historically but not since the 1970s, and which were inside MPAs. The CWCS ecosystems of the Eastern Tropical Pacific have been investigated primarily in Costa Rica and Ecuador (Cortés, 2019). Near the Galapagos Islands, large deep-sea coral reefs (at depths of between 400 m and 600 m) were discovered recently. All studies have been single observations, which makes evaluations of change almost impossible. In addition, CWCS have recently been surveyed in the South China Sea, thereby filling a data gap that previously existed in this region (Ta and others, 2024).

South Pacific Ocean

In addition to long-standing industrial activity, the commercial exploitation of deep-sea mineral resources is an additional threat to CWCS habitats and coral gardens in particular. This is of particular concern in the Central Pacific where most interest has been focused. The potential impacts of mining involve physical destruction of the seabed and damage to the habitat and fauna by mining equipment, as well as changes in seafloor topography and geochemical characteristics in the direct vicinity of the mining site (Carreiro-Silva and others, 2022). The sediment plumes that are generated can affect the entire water column, disperse for hundreds of kilometres and last several years (Muñoz-Royo and others, 2021; Morato and others, 2022). The extent and nature of ecosystem impacts resulting from these plumes are detrimental, with mortality and tissue loss observed in the octocoral *Dentomuricea aff. meteor* (Carreiro-Silva and others, 2022). At present, however, combined effects of these impacts and the impacts of environmental change are poorly understood (Van Dover and others, 2017, 2020).

Southern Ocean

There has been little exploration of CWCS systems in the Southern Ocean in recent years. It should be noted, however, that the presence of the Schmidt Ocean Institute RV *Falkor (too)* will add significant amounts of data from Antarctica, the South Sandwich Islands and other parts of the area of application of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) in 2024 and 2025. Proposals for additional MPAs in East Antarctica, the Weddell Sea and the Antarctic Peninsula have been under negotiation within the Commission for the Conservation of Antarctic Marine Living Resources but consensus on implementation has not yet been reached (Boothroyd and others, 2024). The Commission developed binding measures for the

identification, designation, monitoring and management of fragile benthic ecosystems, including CWCS, in 2007. These ecosystems have been included in the subsequent design of MPAs throughout the area of application of CCAMLR. In addition, the prohibition of high-seas bottom trawling and the targeting of toothfish at depths shallower than 550 m, which entered into force in 2009, closed much of the continental shelf to impacts from bottom contact from fisheries in an effort to avoid significant adverse impacts on CWCS.

4. Key remaining knowledge and capacity gaps and new gaps

Global awareness of the importance of CWCS continues to grow with discoveries of new ecosystems, the services and biodiversity they support and the threats they are under. Research on ecosystem services, climate risks and foundational biodiversity science is being used increasingly in communication efforts. Programmes such as the Deep-Ocean Stewardship Initiative, REV Ocean, OceanX and Ocean Census, as well as the work of the Ocean Exploration Trust with its vessel EV *Nautilus* and the Schmidt Ocean Institute with its vessel RV *Falkor (too)*, have led to increased international expeditions and philanthropic investment, offshore live streaming and increased focus, training and multimedia science communication efforts (art, animation, documentaries, podcasts, etc.), which are helping to increase access and global awareness.

While awareness of CWCS is growing, the deep sea is coming to be seen as a resource for marine CO_2 removal. A number of proposed marine CO_2 removal projects entail storing carbon in the deep sea, but there is a danger in overlooking the ecological complexity of the deep sea or failing to account for the habitats and ecosystem processes that may be affected, including CWCS (Levin and others, 2023). For example, alkalinity enhancement, direct injection of CO_2 or organic carbon deposition could directly or indirectly alter local pH, oxygen levels and sedimentation dynamics, and CWCS, including their larval stages, are potentially sensitive to smothering from an excess of organic matter or mineral deposition (see Levin and others (2023) for a review of these issues).

Looking forward, the conservation and sustainable management of CWCS aligns with the Sustainable Development Goals, particularly Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development. Ecosystem services from CWCS habitats are at risk, including climate regulation, food production and the provision of livelihoods (Morato and others, 2020; Cordes and others, 2023). CWCS also play an indirect and important role in carbon sequestration over the intermediate-term (hundreds or thousands of years) by provisioning their complex skeletons and building the habitats that support a diverse range of marine life, which all contribute to the deep-sea carbon cycle (Bax and others, 2021).

Integrating CWCS into climate adaptation and mitigation policies, through nationally determined contributions, for instance, would aid their role in supporting biodiversity, maintaining ecosystem services and contributing to global decarbonization goals. For example, aligning the Antarctic Treaty System with the Paris Agreement could facilitate the inclusion of Antarctic CWCS conservation targets in nationally determined contributions (Bax and others, 2021). Morato and others (2020) emphasize the need for better integration of climate refugia into spatial management efforts. There have also been improvements in terms of accounting for the ecosystem services provided by cold-water coral habitat (Cordes and others, 2023) and new work to support consideration of these services in climate-smart marine spatial planning (Bravo and others, 2023; La Bianca and others, 2023). This supports ecosystem service-based management.

There is also increasing recognition of the importance of Indigenous knowledge and appreciation for cultural values in understanding and managing deep-sea ecosystems (Escobar and others, 2021). Cultural connections to the deep sea include spiritual connections, and Indigenous coastal communities are expressing increased concern for deep-sea habitats, including CWCS. Policy briefs and arts-based approaches have offered new avenues for understanding, documenting and sharing traditional and Indigenous knowledge (Escobar and others, 2021).

Capacity for monitoring and research is overwhelmingly concentrated in the global North. Most countries lack deepwater monitoring and many lack research vessels, resulting in a dependence on outside technologies and data-sharing. The FAIR data principles (which state that data should be Findable, Accessible, Interoperable and Reusable) are essential for promoting open and equitable data-sharing, and they are complemented by the Collective Benefit, Authority to Control, Responsibility, Ethics framework, under which data collection and sharing

should be conducted ethically, inclusively and with respect for the rights and knowledge of local communities. The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization to the Convention on Biological Diversity provides an important framework to ensure that the benefits arising from samples and data are shared with local communities on a fair and equitable basis.

To support growing observation efforts, technologies that enhance monitoring and protection for management increasingly include autonomous systems (Zelada Leon and others, 2020). These advances support the development of indicators for assessing key deep-sea habitats in national waters and areas beyond national jurisdiction, and effectively reduce habitat disturbance by improving marine spatial planning (Kazanidis and others, 2020; Orejas and others, 2020). Environmental DNA technologies are rapidly advancing and could enable low-cost, non-invasive, efficient monitoring of biodiversity and ecosystem health (McCartin and others, 2022), especially when combined with curated sequence libraries and taxonomic reference collections. In addition to environmental DNA, recent advancements in technology, including crewed submersibles and artificial intelligence, have also significantly enhanced understanding of CWCS. While these tools still face certain limitations, these technologies enable deeper and more detailed exploration, allowing for in situ observations of growth, behaviour and species interactions (Mogstad and others, 2022; Prado and others, 2023; Aguzzi and others, 2024; Gallego and others, 2024; Wang and others, 2024). These advances in technology and data acquisition, in combination with early detection of stressors (such as pollution, temperature changes and invasive species), enable faster management responses, reducing damage to CWCS and potentially preventing habitat degradation.

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Subchapter 5F
Estuaries and deltas

Key points

- Intensified human activities, combined with stronger winds and increasingly frequent extreme events associated with climate warming, have caused complex changes in estuaries and deltas (Venturini and others, 2024).
- Coastal sediment suspension and river plumes increasingly reflect global trends; nevertheless, these changes are highly region-diverse (Laignel and others, 2023).
- Changing estuarine and deltaic environments have significantly altered sediment dynamics (Sengupta and others, 2023), water quality and ecosystem structures (De Souza and others, 2024), exacerbating ecological risks, such as hypoxia and acidification, as well as socioeconomic losses (Zhou and others, 2017; Meng and others, 2022; Ma and others, 2024).
- Governance efforts in estuaries and deltas have resulted in some progress. Local improvements include reduced hypoxia in the Black Sea and Long Island Sound and less eutrophication in the Yangtze River estuary. Ecosystem responses remain slow compared with management intensity, however, reflecting the complexity of multifactorial risks and delays in restoration (Uber and others, 2022; Pein and others, 2023).
- Ongoing efforts are essential for the sustainability of estuarine and deltaic ecosystems. Such efforts should emphasize monitoring, risk forecasting and integrated socioeconomic assessments.

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1. Introduction

Estuaries and deltas are highly complex ecosystems, with diverse hydrodynamic and biogeomorphological profiles, facing considerable ecological and socioeconomic challenges (Laignel and others, 2023). These ecosystems provide numerous significant ecological functions and are particularly biologically productive. Coastal wetlands and other ecosystems offer vital ecosystem services, such as safeguarding coastal populations and infrastructure from erosion, flooding and storms, filtering pollutants and toxins from coastal waters, and supporting fisheries by serving as significant spawning grounds. These systems are among the most affected by human activities, such as land reclamation (Sengupta and others, 2023), eutrophication, invasive species (De Souza and others, 2024) and climate change, the impacts of which include sea-level rise, storm surges, delta subsidence, waves and river flooding (Xuan and others, 2021; Ma and others, 2022).

In addition, such processes as storm surges, waves, high tides, coastal river inundation, groundwater inundation and sea-level rise can lead to significant disasters when several processes occur simultaneously. Many of the world's coastlines are eroding and therefore retreating. The marine ecosystem in estuaries and deltas is also affected significantly by compound weather and climate extremes, which can lead to severe ecological disasters, such as enhanced summertime hypoxia due to heavy precipitation in the Changjiang watershed (Meng and others, 2022; Ma and others, 2024; Zhang and others, 2025).

The present subchapter provides an update to the second *World Ocean Assessment* and serves to highlight the significant challenges faced by estuaries and deltas due to both human activities and weather and climate extremes. Such ecosystems are affected by multiscale oceanic and atmospheric processes in addition to human disturbances, which make their governance more challenging than before.

2. Environmental changes since the second *World Ocean Assessment*

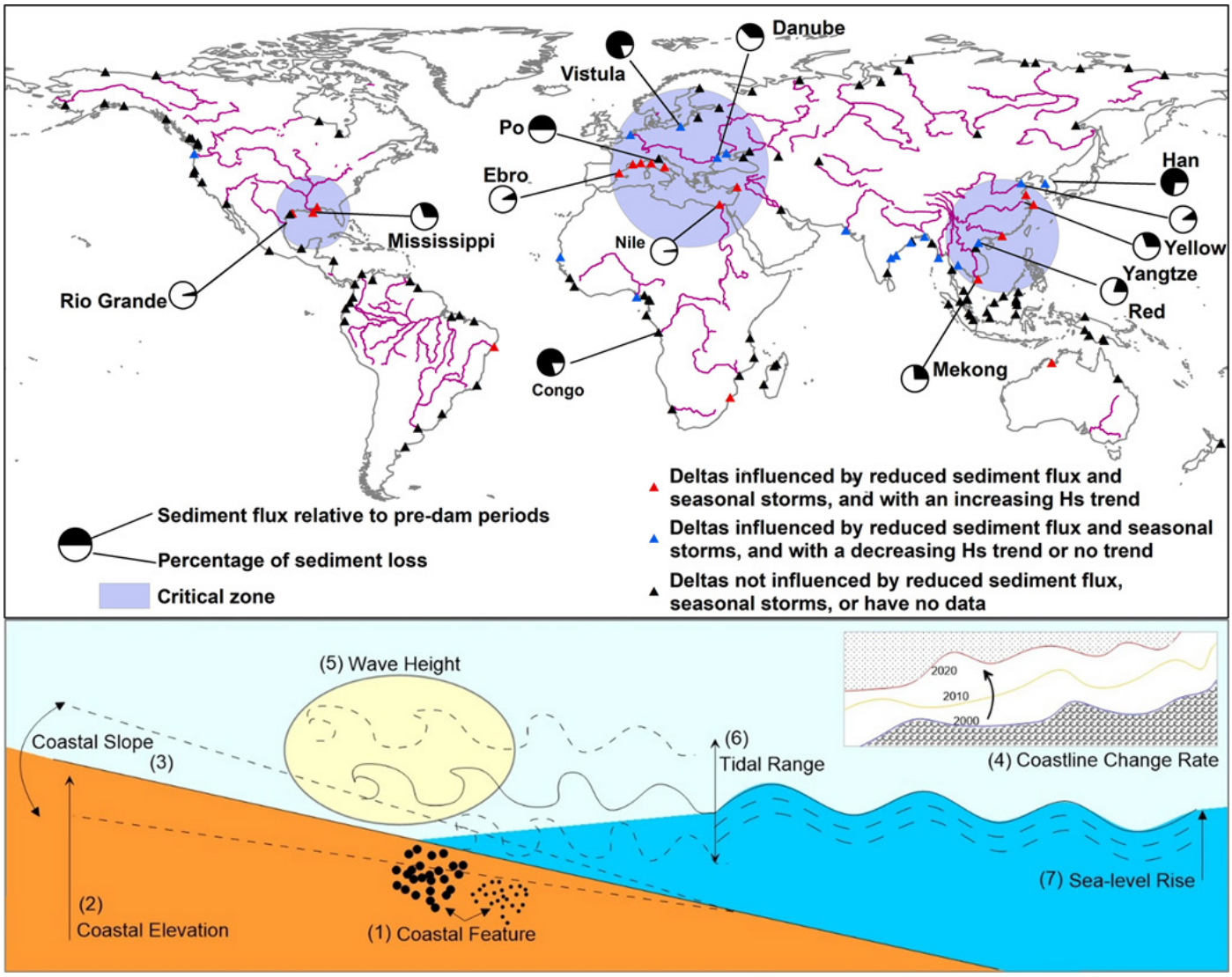
Since the previous assessment, estuaries and deltas worldwide have undergone significant shifts in both physical and ecological states. Anthropogenic impacts on river run-off and suspended sediment flux exhibit strong spatial heterogeneity. In the northern hemisphere, extensive dam construction has reduced riverine sediment loads to about 49% of pre-dam levels, whereas in the southern hemisphere, intensified land-use changes have boosted suspended sediment concentrations by 41 ± 7% compared with the 1980s average (Dethier and others, 2022). As a result, the global riverine sediment supply to the ocean is being rapidly restructured, with the primary source shifting from Asia to South America.

Declining sediment supply poses a serious challenge to many deltas that rely on continuous accretion to offset relative sea-level rise and subsidence (see figure I). Widespread groundwater abstraction, urban development and natural compaction are exacerbating these pressures, accelerating subsidence in large river deltas (Harris and others, 2020; Karlsrud and others, 2020). Where geological instability intersects with ongoing sea-level rise, the net effect often leads to heightened flood risk and coastal retreat (Zhu and others, 2019). In parallel, anthropogenic changes to river discharge – both reductions and occasional increases – can alter estuarine and deltaic circulation patterns, modifying nutrient delivery and affecting biological productivity in nearshore waters.

Climate change adds further stress by intensifying extreme weather and climate events, such as heavy precipitation, droughts, marine heatwaves and tropical cyclones (Iles and others, 2024; Studholme and others, 2022; Li and others, 2024b; Zhao and others, 2024). These events disrupt salinity regimes, shift sediment transport pathways and exacerbate erosion, undermining the stability of deltaic shorelines. There is growing evidence linking climate change to an upsurge in infectious diseases (Tsui and others, 2024) and to shifts in marine species distribution (Duffy and others, 2022; Hutchins and Capone, 2022). Ocean warming, marine heatwaves, eutrophication, acidification and low-oxygen extremes continue to pose significant threats to estuarine and deltaic ecosystems (Guo and others, 2022; Johnson and Lyman, 2020; Li and others, 2024a; Sampaio and others, 2021). In some estuarian areas, severe hypoxia episodes have led to ecological disasters that affect fisheries, benthic habitats and broader food webs (Ma and others, 2024). To mitigate these impacts, local stakeholders are endeavouring to alleviate ecological stresses through engineering interventions and management measures (Meng and others, 2024).

Figure I

Global distribution of deltas influenced by both reduced sediment flux and seasonal storms and seven factors affecting coastal vulnerability



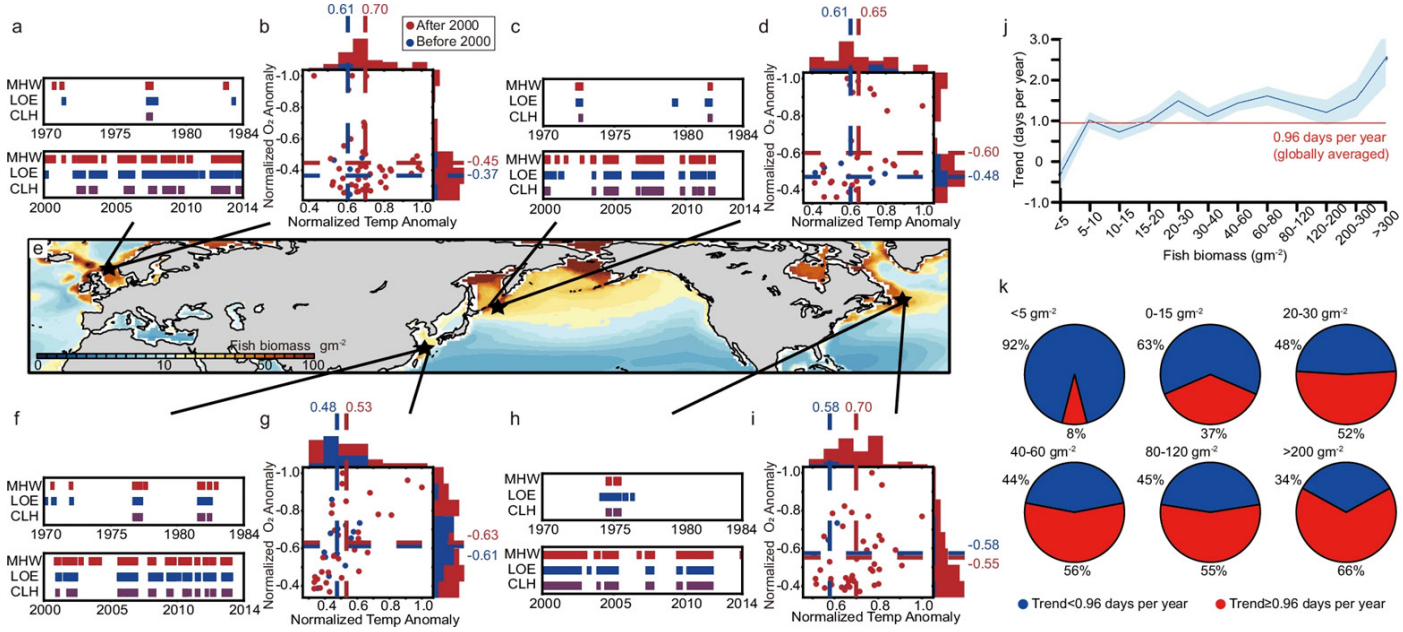
Sources: Zhu and others, 2024; Pang and others, 2023.

Estuaries across the globe have experienced nutrient loading from urban, agricultural and aquaculture sources, prompting eutrophication, harmful algal blooms (Brown and others, 2020) and bottom-water hypoxia (Chen and others, 2020; He and others, 2022; Ke and others, 2022; Zamora-López and others, 2023; Sudradjat and others, 2024; Zhou and others, 2020). While improved wastewater treatment has mitigated problems in some developed regions (Lenstra and others, 2020), the situation in many populous coastal zones continues to deteriorate. Coordinated nutrient management and integrated coastal planning remain key to long-term eutrophication control.

Invasive species represent another serious concern for estuarine and deltaic environments (Hensel and others, 2021; Ren and others, 2021). Maritime traffic and trade facilitate introductions, while warming waters expand the suitable habitat range for non-native organisms (Norton and Norton, 2021). Effective control hinges on targeted removal strategies and understanding complex ecological interactions (Creed and others, 2021; Liu and others, 2023).

Figure II

Compound low-oxygen extreme and heatwave events in relation to marine fish biomass



Source: Li and others, 2024a.

In addition to ecological shifts, geomorphological and hydrological changes require high-resolution monitoring. Accurate bathymetric and shoreline data are vital for understanding erosion, deposition and coastal flooding patterns, yet an estimated 70–80% of the global coastal zone lacks reliable bathymetric coverage (McCarthy and others, 2022). This gap impedes the ability to develop marine planning strategies, forecast coastal hazards, manage navigation channels and design adaptive measures for aquaculture or infrastructure protection (Han and Zhou, 2025). In locations with pronounced sediment deficits, even small errors in bathymetric data can lead to the underestimation of erosion rates and thus exacerbate vulnerabilities to storm surges or sea-level rise.

Overall, the global picture since the second *World Ocean Assessment* is one of mounting pressures on estuaries and deltas from multiple sources. Anthropogenic activities (including dam construction, intensive groundwater pumping, sediment extraction and land-use changes) have reshaped sediment fluxes and accelerated subsidence in many heavily populated deltas. Pollution problems are prevalent in those systems with high population density. Inadequate investment in pollution control exacerbates these issues, particularly in underdeveloped areas. These problems often coexist, demonstrating the interconnectedness of hydrogeomorphic processes, ecological processes and economic development. Concurrently, a warming climate has amplified extreme events, contributing to erosion, salinity regime alterations and more frequent low-oxygen conditions and marine heatwaves. Meanwhile, emerging challenges, such as invasive species, underscore the delicate balance of these interconnected ecosystems. As these trends intensify, the combination of physical alterations, biogeochemical perturbations and shifting species distributions will continue to transform estuarine and deltaic environments worldwide.

3. Region-specific changes

Arctic Ocean

Over 387 deltas, including the Lena Delta in the Russian Federation and the Mackenzie Delta in Canada, filter sediment and carbon fluxes from the Arctic landscape to the ocean (Mann and others, 2022). Compared with lower-latitude deltas, Arctic deltas have subdued morphodynamics due to ice cover. The warming climate has led to an expansion of the open-water season in Arctic deltas, however, which has caused increased wave influence and unknown changes in sediment transport and carbon cycling (Overeem and others, 2022). Nevertheless,

Greenlandic deltas experience weak wave impacts because of the enclosed topography of their locations. The elongated open-water season is potentially inducing increased sediment loading (Bendixen and others, 2019), leading to a mean progradation rate of 0.011 km^2/year for the 75 Greenlandic deltas (Overeem and others, 2022).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

Several deltas are experiencing significant changes due to subsidence, erosion and human interventions. Subsidence rates have reached 16 mm/year in the Mississippi Delta (Harris and others, 2020) and 12–20 mm/year in the Nile Delta (Rateb and Abotalib, 2020). Erosion is worsened by extreme weather, especially in the Mississippi and Elbe Deltas (Zhu and others, 2024; Uber and others, 2022). Dam construction and river modifications have reduced sediment delivery, slowing delta growth in the Rhône and Danube Deltas (Mikhailova and Isupova, 2006; Constantinescu and others, 2023). Saltwater intrusion affects the Rhône and Nile Deltas, while ecological degradation is evident in the Dnieper Delta (Minaieva and Korzhov, 2024). Effective management is critical for restoration (Uber and others, 2022; Pein and others, 2023).

South Atlantic Ocean and wider Caribbean

The ecosystem of the Amazon Delta is largely intact, supporting diverse species and transporting between 2.3 billion and 3.1 billion tons of sediment annually, aiding coastline growth without significant subsidence. It should be noted, however, that population growth and sea-level rise will require improved management (Anthony and others, 2021).

The River Plate estuary, one of the largest estuarine systems in South America, is experiencing continuous but moderate sea-level rise and has suffered an extraordinary increase in the flow of the main tributaries since the early 1970s. The frequency of extreme events, mainly wind-induced storm surges, has risen over the past three decades. At present, anthropogenic eutrophication (caused by nutrient inputs linked to human activities) is one of the most important environmental impacts on the ecosystem's health and services. Massive cyanobacteria blooms promoted by nutrient enrichment associated with hydrological, oceanographic and meteorological factors have been reported more frequently in recent years, generating a loss of water quality, cultural ecosystem services and tourism revenues (Venturini and others, 2024).

The Niger Delta has seen significant coastline retreat, in particular during the periods 1950–1987 and 2007–2012, linked to run-off changes and human activities (Dada and others, 2018). The Congo River basin faces future drought and food scarcity risks, necessitating adaptive measures (Karam and others, 2023).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

The Ganges-Brahmaputra-Meghna Delta faces risks from climate change, extreme hazards and human activities, including a subsidence rate of 5.6 mm/year. Riverbank erosion displaces 300,000 people annually, damaging land and infrastructure (Paszkowski and others, 2021). While sediment supply generally offsets sea-level rise, dams and water diversions threaten this balance, making upstream sediment management crucial (Raff and others, 2023). The Indus Delta has seen a decline in organic carbon fluxes due to damming and reduced river discharge, worsened by coastal erosion and changing monsoon patterns (Ahmed and others, 2021). Human activities, such as sediment mining, have caused erosion in the west and accretion in the east (Chen and others, 2020). The Ganges-Brahmaputra-Meghna Delta also faces severe subsidence (20 ± 10 mm/year), increasing the risk of sea-level rise (Steckler and others, 2024).

North Pacific Ocean

Dams and sediment mining have reduced suspended sediment in Asian estuaries, worsening coastal ecosystem degradation (Yunus and others, 2022). The Mekong Delta faces subsidence (17–44 mm/year) due to over 130 dams and groundwater extraction (Hecht and others, 2019). The expanding coastline of the Yangtze Delta shows declining sediment concentrations and worsening hypoxia (Ma and others, 2024). The Pearl River estuary suffers severe subsidence (~87.3 mm/year; Liu and others, 2023), while the Yellow River Delta faces erosion from reduced sediment supply (Zhu and others, 2024). In Osaka Bay, warming has caused a shift in fish distributions. Overall, human activities, such as dams, sediment extraction and land reclamation, are key drivers of these environmental changes.

South Pacific Ocean

Sediment transport from the deltas to the ocean has generally increased in the South Pacific Ocean, especially in Australia (Hou and others, 2024). For example, despite dam-building upstream of the Burdekin River, located in the dry tropics of north-east Australia, coarse sediments downstream of the dam have reached the river delta. The riverbed of the Burdekin River Delta has risen measurably in the past few decades, which has caused an increase in flood levels of approximately 1 m (Wolanski and Hopper, 2022). The trapping of sediment in the delta has induced erosion of the offshore Cape Bowling Green Peninsula, which has fundamental ecological impacts on the coastal ecosystem.

Southern Ocean

The surfaces of ice shelves in Antarctica melt during the austral summer; for instance, the meltwater volume reached as high as 0.83×10^9 m^3 in the summer of 2016/2017 on Amery Ice Shelf (Spergel and others, 2021). The meltwater forms surface lakes on the sea ice, which play essential roles in the surface energy balance of sea ice (Dell and others, 2024). Increased surface meltwater on ice shelves associated with climate warming may trigger the development of estuaries in Antarctica, which could lead to accelerated ice loss and sea-level rise (Boghosian and others, 2021).

4. Key remaining knowledge and capacity gaps and new gaps

Intensified human activities, coupled with climate change, have exposed estuaries and deltas to severe hydrological and ecological threats. Human activities (such as dam-building and groundwater extraction), natural subsidence of deltas and climate-associated sea-level rise are gradually squeezing the inland space of coastal zones. Inland flooding, compounded by astronomical high tides, may cause substantial losses to coastal zones and surrounding megacities. In addition to inland flooding, extreme estuarine upstream droughts compounded by astronomical high tides cause serious saltwater intrusion that threatens drinking water safety by affecting the drinking water reservoirs of megacities in coastal zones. Global warming has caused extreme atmospheric and oceanic events to occur with higher frequency. Populations are increasingly concentrated in coastal areas, which may put stressed ecosystems and local environments at higher risk, entailing greater complexity and uncertainty.

Socioeconomic structures directly influence human activities, which have significant impacts on the sustainability and resilience of estuarine and deltaic systems. In return, estuarine and deltaic environments influence the societies and economies of coastal zones in multiple and complex ways, which could potentially require restructuring. It is difficult to project how societies and economies in coastal zones will change in the future. It would be even more difficult to forecast the effects of feedback from local marine ecosystems, as well as estuarine and deltaic environments, to coastal societies and economies. Integrated monitoring systems and scientific investigations can effectively advance a comprehensive understanding of inland areas and estuary or delta systems as a continuum. Science-based cooperation, planning and strategy are required to build sustainable and resilient estuarine and deltaic systems.

Both short- and long-term strategies are urgently needed for the sustainable development and use of both inland and coastal zones. Existing modelling cannot provide timely early warnings of extreme events or accurate long-term predictions of their occurrence in coastal zones. Although theories regarding two-way feedback between upstream activities and estuarine or deltaic environments are improving, integrated monitoring systems and engineered protections can also be beneficial, especially during short-term emergency response and mitigation. Integrated planning of emergency responses to extreme events by coastal megacities is required in order to reduce losses effectively. Public science education can help people to utilize resources sustainably and respond effectively to extreme events, such as storm surges and flooding. Long-term integrated investigations are crucial for sustaining estuarine and deltaic environments and the ecosystem services they provide for human well-being. A comprehensive database and improved modelling, offering reliable tools for short-term predictions and long-term projections, are essential for the sustainability and resilience of estuarine and deltaic services.

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Ellen Cuylaerts

Subchapter 5G
Seagrass meadows

Key points

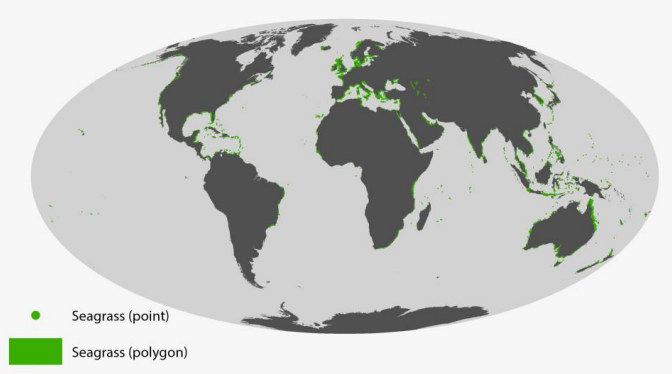
- Seagrass meadows are experiencing accelerated degradation due to urbanization, pollution and climate change, leading to a decline in their extent, biodiversity and ecological function.
- Seagrass meadows play a crucial role in carbon storage, habitat provision and water quality improvement, yet their functions are not widely recognized or fully utilized.
- There are insufficient systematic monitoring, protection and restoration technologies for seagrass meadow degradation, with insufficient scientific knowledge and policy support, highlighting the need for enhanced international collaboration and capacity-building.

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1. Introduction

Seagrass meadows are found across all climatic zones except Antarctica[1] (see figure I), providing essential services, such as carbon sequestration, climate regulation, nutrient cycling and habitat for various marine species. Despite their importance, these ecosystems are facing alarming rates of decline, with an estimated 29% of their global extent lost since records began in 1879 (Waycott and others, 2009). The primary causes of this decline include poor water quality, physical disturbances, coastal development and overfishing. These pressures have placed seagrass meadows among the most threatened ecosystems globally, alongside mangroves, coral reefs and tropical rainforests. Urgent and effective management strategies are needed to reverse this loss and preserve the critical role of seagrasses in maintaining coastal biodiversity and resilience. The present subchapter emphasizes ecosystem-level changes in seagrass meadows from 2018 to 2023, covering environmental change, contributing factors, socioeconomic impacts and the knowledge gaps in addressing these changes. It is focused on conditions, trends and responses, rather than taxonomy or species diversity.

Figure I
Global distribution of seagrass



Sources: United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) and Short, 2021.

2. Environmental changes since the second *World Ocean Assessment*

Changes in overall status

Estimates of the global seagrass area range between 160,387 km² and 266,562 km² (McKenzie and others, 2020), though measuring losses remains challenging. Dunic and others (2021) found that individual meadows lose 1–2% of their area annually, with larger meadows (>1,000 ha) declining more slowly. Europe, North America, Japan, China and South-East Asia face the greatest risks. Between 2000 and 2020, 60% of seagrass meadows in South-East Asia (68 sites across nine regions) declined by 10.9% annually, while 20% increased by 8.1% annually (Sudo and others, 2021).

Factors contributing to the changes observed

Seagrass decline is predominantly driven by poor water quality and coastal development (Dunic and others, 2021). Coastal development leads to both direct impacts, such as habitat loss due to port construction, and indirect impacts, such as reduced light availability from sediment plumes caused by dredging activities. Light deprivation caused by nutrient-induced algal growth and sedimentation compromises photosynthesis. Destructive fishing practices, including unsustainable bottom trawling in vulnerable habitats can also cause losses, with heavy equipment damaging seagrass habitats. Other methods, including seining and gleaning, also contribute to losses in some areas (Mwikamba and others, 2024). Climate change is an increasing threat, with rising temperatures and intensified storms (Wernberg and others, 2024) leading to significant seagrass loss. Marine heatwaves and storms have already caused extensive damage (Correia and Smee, 2022; Strydom and others, 2020). In addition, climate change may alter the distribution of herbivores and pathogens, further affecting seagrass health (Wernberg and others, 2024). Overgrazing by herbivores, such as sea urchins and sea turtles, has led to seagrass decline in multiple regions of the Atlantic, Indian and Pacific Oceans. Mitigating these pressures and restoring seagrass meadows is now a pressing conservation challenge. Restoration efforts, combined with efforts to address the root causes of

[1] See https://data.unep-wcmc.org/datasets/7.

decline, have demonstrated the potential for substantial seagrass recovery in several regions (Fernandes and others, 2022; Orth and others, 2020).

Impacts of the changes on and interactions with other components of the marine system

Seagrass ecosystems are shaped by interconnected factors, such as herbivory, climate change, habitat connectivity and interspecies interactions. Rising sea temperatures and ocean acidification due to climate change affect species distribution and seagrass productivity (James and others, 2023; Beca-Carretero and others, 2022). Herbivory by sea turtles and fish plays a critical role in regulating seagrass dynamics, with shifts in herbivory patterns observed in the Mediterranean (Santana-Garcon and others, 2023). Habitat connectivity supports organism movement and genetic exchange, strengthening ecosystem resilience (de Fouw, 2018). In addition, seagrass meadows play a crucial role in sediment storage and carbon export, sometimes over hundreds of kilometres (Huxham and others, 2018), highlighting their importance for coastal sustainability and ecosystem health.

Social, economic and cultural aspects of the changes

On the social front, seagrasses support livelihoods, especially in small-scale fisheries, ensuring food security for millions (Unsworth and others, 2019). On the economic front, seagrasses protect coastlines, enhance the productivity of fisheries, sequester carbon and stabilize sediment. On the cultural front, they are integral to Indigenous and local traditions, shaping fishing practices, rituals and community identities (Nordlund and others, 2016). The degradation of seagrass ecosystems disrupts biodiversity and socioeconomic benefits, with reduced fisheries productivity threatening economic stability and eroding cultural ties, thereby undermining community resilience.

Although public awareness of the importance of seagrasses has increased (Cullen-Unsworth and Unsworth, 2018), full recognition of their value among all stakeholders has yet to be achieved (United Nations Environment Programme (UNEP), 2020). Seagrass restoration efforts are becoming more common, however, often involving local communities. This increased focus on seagrasses has also led to their more frequent inclusion in management plans (Nordlund and others, 2016). Effective management requires a deeper understanding of seagrass dynamics and reliable baselines. Implementing policies that balance ecological, economic and cultural needs is essential to ensuring the long-term resilience of both ecosystems and the communities that depend on them (Unsworth and others, 2019).

In addition, such programmes as the Dugong and Seagrass Conservation Project[2] funded by the Global Environment Facility, the Convention on the Conservation of Migratory Species of Wild Animals, the Memorandum of Understanding on the Conservation and Management of Dugongs (*Dugong dugong*) and their Habitats throughout their Range[3] and the Seagrass Ecosystem Services Project[4] funded by the International Climate Initiative support conservation projects in countries by promoting coordinated, international action to ensure the long-term survival of dugongs and the associated seagrass habitats they depend on.

Implications for achieving the Sustainable Development Goal targets

Seagrasses contribute to several Sustainable Development Goals, including carbon sequestration and disaster resilience (Goal 13), protection of coastal communities (Goal 11) and food and economic security (Goal 10), while promoting sustainable use (Goal 12), marine conservation (Goal 14) and partnerships (Goal 17) (see General Assembly resolution 70/1). Their value was highlighted in the UNEP report entitled *Out of the Blue: the Value of Seagrasses to the Environment and to People* (UNEP, 2020). Seagrass conservation efforts, including the 2030 Seagrass Breakthrough project announced at the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change, align with global climate commitments and all 10 targets associated with Goal 14.

2 See www.dugongconservation.org.
3 See www.cms.int/dugong/en/page/mou-text-0.
4 See www.seagrasswatch.org/iki-seagrass-ecosystem.

3. Region-specific changes

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

In the north-western Atlantic, *Zostera marina* dominates in the north, while *Syringodium filiforme* is prevalent in the south, leading to research and restoration efforts shifting along a latitudinal gradient. While *S. filiforme* populations remain stable, *Z. marina* has experienced declines due to eutrophication, sedimentation and climate warming. In the north-eastern Atlantic, including the Baltic, Black, Mediterranean and North Seas, research has focused on dominant species, such as *Z. marina* and *Posidonia oceanica*, with effort particularly concentrated in western Europe and the Mediterranean. Between 1869 and 2016, Europe experienced a net loss of 35,000 ha of seagrass area, though recent trends show slower losses and some gains (de los Santos and others, 2019), such as *Z. marina* recolonizing the Mira Channel in Portugal (Guerrero-Meseguer and others, 2021). Restoration efforts, such as the recovery of 40,000 ha of seagrass in the Chesapeake Bay, United States of America, offer hope. In Europe, however, outdated or incomplete spatial data – mainly covering the Natura 2000 network – are hindering accurate tracking of seagrass changes, making it difficult to assess both losses and gains comprehensively (Huber and others, 2024; Poursanidis and others, 2023).

South Atlantic Ocean and wider Caribbean

Understanding of seagrass meadows in the South Atlantic Ocean and the wider Caribbean remains limited. Although the region has historically experienced significant seagrass losses, recent trends indicate a balance, with losses matching gains. *Thalassia testudinum* forms extensive, dense and stable beds, but when disturbed it is replaced by faster-growing species, such as *S. filiforme* and *Halodule wrightii*, all classified as being of least concern. In 2022, a vast seagrass ecosystem, covering between 66,000 and 92,000 km², was discovered on the Bahamas Banks (Gallagher and others, 2022). Of the 18 seagrass species in the region, *Halodule bermudensis* and *Halodule ciliata* are critically endangered, with several others near threatened or vulnerable. Seagrass abundance has drastically declined across the Bermuda Platform due to overgrazing by sea turtles (Fourqurean and others, 2019). In addition, *Halophila ovalis* and *Halophila stipulacea* are invasive species expanding in the Caribbean (Winters and others, 2020). Global climate change is also causing shifts in the distribution of some species, such as *H. wrightii* and *Halophila decipiens*, as tropicalization alters habitat conditions.

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

East Africa, which has 14 recorded seagrass species, faces seagrass decline due primarily to the use of destructive fishing techniques, such as seine fishing, in sensitive areas. The collection of gastropods and crustaceans further disturbs seagrass meadows (Chitará-Nhandimo and others, 2022; Amone-Mabuto and others, 2023; Mwikamba and others, 2024). In Maputo Bay, Mozambique, seagrass cover decreased by 33.4% between 1991 and 2023 due to anthropogenic disturbances (Amone-Mabuto and others, 2024). In Kenya, *Thalassodendron ciliatum* has experienced significant decline due to the proliferation of sea urchins (Uku and others, 2021). In southern Mozambique, *Thalassodendron leptocaule* is considered near threatened, while *Zostera capensis* in South African estuaries is endangered (Duarte and others, 2012; Adams and van der Colff, 2018). In the Persian Gulf and Red Sea, research gaps hinder comprehensive understanding of seagrass ecosystems, though recent studies have recorded *Halophila decipiens* in Iraqi waters for the first time, expanding known biodiversity (Ibrahim, 2021). The invasion of *Halophila stipulacea* from the Red Sea to the Mediterranean highlights ecological shifts (Nguyen and others, 2018), while unique evolutionary processes in *Halophila ovalis* populations in the Red Sea underscore the region's distinct biodiversity. In addition, the discovery of *Halophila beccarii* in the Bangladeshi part of the Bay of Bengal emphasizes the importance of continued marine assessments (Haque and others, 2024).

North Pacific Ocean

In the north-eastern Pacific, *Z. marina* is the dominant seagrass species, ranging from the Arctic to Mexico, where it coexists with *Ruppia maritima* and the invasive *Zostera japonica*. A recent genetic split of *Zostera pacifica* from *Z. marina* leaves the population status of this species uncertain. Localized seagrass declines in this region are attributed to coastal development and eutrophication. Similarly, since 2000, seagrass beds across South-East Asia and East Asia have experienced significant losses, with over 60% declining at an annual rate of 10.9%, due in large part to human activities and

natural factors (Sudo and others, 2021). The widespread degradation of South-East Asian seagrass ecosystems is further exacerbated by significant knowledge gaps with respect to subtidal seagrass meadows, which limit effective conservation strategies and result in a persistent disconnect between scientific research, policy and management implementation (Fortes, 2018).

South Pacific Ocean

Seagrass meadows are found in 17 of the 22 Pacific island countries and territories, with the highest species richness in Papua New Guinea, which hosts 13 species. It should be noted, however, that seagrasses remain understudied compared with coral reefs and mangroves. Recent studies from the period 2018–2023 highlight increasing threats to these ecosystems, in particular from coastal development, pollution and climate change. For instance, seagrass cover in parts of Fiji and Solomon Islands has declined due to land-based pollution and destructive fishing practices. There are also emerging threats from habitat loss, with projections suggesting a 5–20% loss in seagrass habitat by 2035 (Waycott and others, 2009). Over 5% of seagrass extent has been lost in Australia since the 1930s, with substantial losses of temperate *Posidonia* species (Statton and others, 2018). *Posidonia australis* in parts of New South Wales is now listed as a threatened ecological community under Australian legislation. Tropical and subtropical seagrass meadows have also been lost, with substantial losses following extreme storm events with very heavy rain, causing run-off and high turbidity. Multiple restoration efforts are now under way around Australia, with the success of efforts steadily improving (Sinclair and others, 2021).

4. Key remaining knowledge and capacity gaps and new gaps

Key changes in knowledge and understanding gaps

A key knowledge gap recognized by seagrass scientists and managers today is how to raise societal awareness about the global significance of seagrasses, which remain relatively unknown (Unsworth and others, 2019). This is a pressing challenge, as increasing awareness can lead to broader support for seagrass conservation, citizen science, informed decision-making on marine biodiversity, improved funding for research and management, and ultimately a healthier planet (UNEP, 2020). Engaging the public through education and collaboration with communication experts is crucial for achieving this. While advances have been made in seagrass mapping and monitoring, in particular with remote-sensing technology (Traganos and others, 2022), significant gaps remain with respect to understanding the distribution of seagrasses in the tropical Atlantic, Pacific, Indian and Southern Oceans, especially in deep or turbid waters. Knowledge of seagrass ecosystem services has improved in some regions, but remains incomplete in many others (Creed and others, 2023). In addition, economic assessments are limited and often undervalue seagrass systems. Better models linking ecological and economic factors are needed for a more integrated approach. Identifying local drivers and stressors continues to be a challenge in relation to targeted management efforts, and there is still limited understanding of how seagrasses will adapt to climate change, particularly under the combined pressures of human activities and environmental shifts.

Key changes in capacity gaps

In addition to knowledge gaps, significant capacity gaps exist in the management of seagrass ecosystems, especially as regards habitat mapping, centralized data repositories, restoration and management frameworks.

(a) **Habitat mapping and monitoring.** Accurate and up-to-date information on seagrass distribution is essential for effective conservation. The current global seagrass map is outdated, and reports of habitat loss (Dunic and others, 2021; Sudo and others, 2021; Adi and others, 2024) highlight the need for improvement. New tools, such as drones, artificial intelligence and cloud-based platforms, are enhancing seagrass mapping capacity, especially on the regional and local scales (Malerba and others, 2023).

(b) **Centralized data repositories.** As seagrass research expands, the volume of data grows significantly (Strydom and others, 2023). However, cross-platform incompatibility continues to hinder efficient data exchange. Establishing a centralized repository with a standardized framework would streamline integration and improve access to seagrass data across various platforms.

(c) **Restoration.** Seagrass restoration is a key nature-based solution for climate change mitigation, but projects often fail due to challenges in relation to site selection, seed germination and maintenance (Unsworth and others, 2023). Scaling up restoration efforts requires practical, simple methods and a better understanding of the interactions among the diverse components of seagrass ecosystems to improve success rates (Orth and Heck, 2023).

(d) **Management framework**. Effective management of seagrass ecosystems requires strong legal, policy and planning frameworks. These vary widely across countries, from well-developed systems, such as those of Canada (Murphy and others, 2021), to ineffective or non-existent policies, as seen in Belize and India (Acharyya and others, 2023; Grimm and others, 2023). Robust frameworks are necessary in order to allocate resources (including funding, personnel and law enforcement) to seagrass conservation.

Remaining gaps

While significant progress has been made in understanding seagrass biology and ecology (Orth and Heck, 2023), several knowledge gaps remain. These relate to such areas as developing cost-effective technologies for habitat mapping and monitoring with improved spatial-temporal accuracy, as well as innovations in seagrass restoration techniques, from site selection to habitat maintenance. The impacts of climate change on seagrasses, particularly in temperate and tropical regions, and the role of seagrasses in carbon sequestration and emissions are still not fully understood. Furthermore, there is a lack of coordination and transparency in global seagrass observations, which limits collective understanding of seagrass ecosystems and the drivers of change. Making seagrass data more accessible, standardized and easily shareable across platforms would greatly enhance efforts to better understand and conserve seagrass habitats worldwide.



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Subchapter 5H Mangroves

Key points

- Global mangrove coverage of 147,000 km^2 spread across 128 countries reflects an increase since the second *World Ocean Assessment*, in which coverage was reported across 118 countries.
- Mangroves are continuing to decrease globally, with the main driver of change being aquaculture, which has resulted in a 21% loss of mangrove cover.
- Mangroves are increasingly facing threats from rising sea levels and severe human-induced pollution, including nitrogen.
- Conservation efforts, including mangrove plantation, ecological restoration and nature inspired solutions, such as sustainable mangrove fisheries, provide an optimistic view of global mangrove protection.

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1. Introduction and context

Mangroves, which are found throughout the world, represent a unique ecotone that bridges land, freshwater, ocean and atmosphere (as discussed in the first *World Ocean Assessment*). Mangroves harbour rich biological diversity and provide ecosystem services, such as support for livelihoods and protection from floods, with a total economic value of at least $65 billion annually (Hagger and others, 2022). This biotope is integral to the rich cultural heritage of Indigenous and local communities and vital for intergenerational conservation of the Indigenous, traditional owner and local community knowledge of those who live along the world's coastlines (Faridah-Hanum and others, 2018; Freiss and others, 2020; Longépée and others, 2021; Moore and others, 2022). Moreover, mangroves protect other coastal biotopes and human settlements against waves, cyclones and flooding (Trégarot and others, 2021). Geographically, mangroves are spread across 128 countries and cover a total area of approximately 147,000 km^2 (Leal and Spalding, 2024). Alarmingly, only 40% of the world's remaining mangrove forests are protected, despite being a part of coastal blue carbon ecosystems and sequestering 168 g of carbon per m^2 per year (Enevoldsen and others, 2024). The rate of net mangrove loss decreased by 44% over the past two decades, falling from 181.5 km^2 per year between 2000 and 2010 to 102.4 km^2 per year between 2010 and 2020 (see the second *World Ocean Assessment*, and Leal and Spalding, 2024).

2. Biodiversity of global mangroves

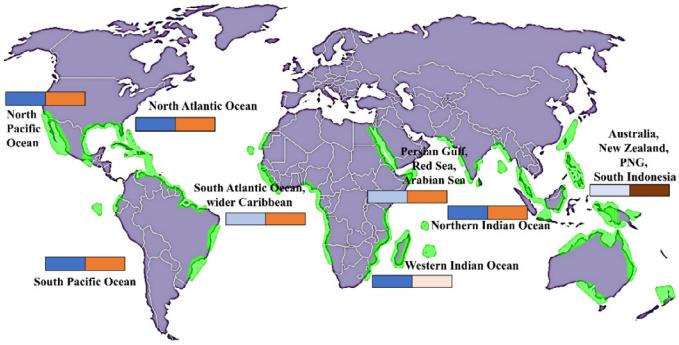
Globally, there have been systematic efforts to document the biodiversity of mangroves, with an emphasis on mangrove plants. According to subchapter 6G of the second *World Ocean Assessment*, there are 65 "valid" or correct names of mangrove taxa in 14 families, inclusive of five hybrids. As of 2024, 82 mangrove plant taxa have been reported, including hybrids (Duke, 2020; Duke and others, 2023; Leal and Spalding, 2024).[1] Mangrove plants are also covered in subchapter 4H of section 4 of the present *Assessment*, with their occurrence in estuaries and deltas further detailed in subchapter 5F. Mangroves are key for other biodiversity attributes, such as their rich fisheries (Reis-Filho and others, 2019) and range of benthic invertebrates (see subchap. 4C). As part of the biodiversity pool, the microbiomes present across diverse microniches within mangroves, including the plant rhizosphere, are important players in maintaining overall ecological health, yet less documented globally (Ghosh and Bhadury, 2018; Allard and others, 2020). The impact of mangroves on the carbon budget is discussed extensively in subsection 5B, chapter 1.

3. Environmental changes since the second *World Ocean Assessment*

There has been a general decline in global mangrove cover since the second *World Ocean Assessment*, albeit with some exceptions. The trends in changes of mangrove cover, as well as potential threats, have been highlighted under respective oceanic regions in figure I, in which documented changes in mangrove cover are clearly emphasized, along with the drivers of such changes for those regions, as well as for adjacent ecosystems from designated ocean systems for the period between 2018 and 2021. In the past decade, aquaculture contributed to mangrove loss of 21%, which is approximately 10% less than in the previous decade (Leal and Spalding, 2024). Sea-level rise is one of the prominent factors that could affect global mangroves, and it has been projected that 25% of mangroves will be submerged in the next five decades.[2]

[1] See also https://iucn.org/our-union/commissions/group/iucn-ssc-mangrove-specialist-group.
[2] See https://iucn.org/node/33749/red-list-mangrove-ecosystems.

Figure I
Causes of loss of mangrove cover across major oceanic regions



Source: Prepared by the writing team.

Note: The following colour coding has been applied: (a) light blue indicates that anthropogenic causes are not the main driver of mangrove loss; (b) dark blue indicates that anthropogenic causes are pertinent; (c) dark orange indicates that natural causes are the main driver of mangrove loss; (d) light orange indicates that natural causes are one driver of mangrove loss; and (e) brown indicates that natural causes are the sole drivers of mangrove loss.

4. Region-specific changes

North Atlantic Ocean

Mangroves in the North Atlantic region, encompassing parts of the Caribbean, the Gulf of Mexico and parts of West Africa, experienced both positive and negative changes between 2018 and 2023. In the North-West Atlantic Ocean, mangroves covered an area of approximately 17,408 km^2 in 2020, representing 11.8% of global mangrove cover. In the Caribbean Sea and surrounding regions, mangrove cover has shrunk to 7,000 km^2 and may disappear within the next few decades (Caribbean Biodiversity Fund, 2025). Until 2020, Cuba had reported an increase of 115,000 ha of mangroves.[3] The main factors that contributed to the changes observed were rapid coastal urbanization, pollution (mainly from industrial discharge), agricultural run-off and disposal of plastic waste. Climate change impacts, such as sea-level rise and increased storm frequency, have resulted in erosion and the submergence of mangrove habitats. Changes in precipitation patterns have affected salinity and resulted in stress for mangroves. Conservation efforts, including the designation of protected areas and community-based initiatives, have helped to stabilize and improve mangrove cover in The Bahamas and Cuba. In the Caribbean, mangroves are central to ecotourism and artisanal practices, and they hold immense cultural significance, in particular for Indigenous Peoples and communities of African descent. It has been observed that 4% of mangroves are showing signs of degradation and this may increase to 12% in next 50 years.[4] By 2060, 75.9% of the mangroves could become submerged.[5]

South Atlantic Ocean and wider Caribbean

The mangroves of the South Atlantic Ocean, which encompasses South America and the wider Caribbean, represent around 26% mangroves globally. There has been an average decline of 0.33% per year in mangrove cover in the Caribbean, which was estimated to stand at 6,031.3 km^2 in 2020 (Bunting and others, 2022). Satellite data for the three decades to 2018 show that mangroves in Brazil are distributed across 9,000 km^2 (Diniz and others, 2019). An estimated sea-level rise of 0.4–0.6 cm, an increase in salinity, changes in sediment flow, geomorphic changes and a 20–30% reduction in rainfall have resulted in mangrove loss (Rull, 2022). Major human-induced drivers are shrimp farms and salt production, accounting for between 38% and 50% of mangrove loss (Diniz and others, 2019). Other marine ecosystems in the region, such as Caribbean coral reefs, are also showing signs of bleaching due to an increase in temperature, as well as the loss of mangroves that had acted as a buffer. Overall, there have been changes due to landward migration of mangroves. Net mangrove loss in this region stands at 3.7% and is projected to increase to a net loss of 6.7% over the next 50 years. It is estimated that approximately 10.5% of mangrove cover will be submerged by 2060.[6]

3 See www.cepal.org/en/publications/44265-effects-climate-change-coastal-areas-latin-america-and-caribbean-evaluation.
4 See https://iucn.org/.
5 Ibid.
6 Ibid.

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Mangroves cover a broad geographical area in the Indian Ocean, including the Western Indian Ocean and the Northern Indian Ocean in particular. By 2020, overall mangrove forest coverage had fallen to 745,518 ha (from a total of 752,650 ha in 2018 and 775,675 ha in 1996), representing a general loss of 7,132 ha (0.95%) between 2018 and 2020 (Erftemeijer and others, 2022). In Kenya and Madagascar, mangroves experienced a slight increase in coverage of 110 ha (0.2%) and 346 ha (0.12%), respectively. Mozambique and the United Republic of Tanzania experienced a loss of 6,825 ha (2.2%) and 755 ha (0.68%) of mangrove cover, respectively (Erftemeijer and others, 2022). The increase in mangrove cover in Madagascar was due to accretion, alluvial deposits and sustained conservation efforts (Bardou and others, 2024). Cyclones have led to the loss of mangroves in Mozambique (Macamo and others, 2016). In the Western Indian Ocean, the loss of mangrove forests is driven by timber and aquaculture activities (Nyangoko and others, 2022), along with pollution (Hamza and others, 2020). Extreme weather events have led to mangrove degradation, including diebacks (Ramarokoto and others, 2024). Mangroves in the Western Indian Ocean are closely interlinked with seagrass meadows and coral reefs where mangroves tend to face towards land-ocean boundaries (Nyangoko and others, 2022). Mangrove losses in the Western Indian Ocean have affected fish and fisheries products, among others. In the Red Sea and the Gulf of Aden, mangroves cover an area of 189.2 km^2 and represent 0.1% of global mangroves. It is interesting to note that mangrove cover in this region has declined by only around 4% over the past decade. Moreover, 1.7% of the region's mangroves are undergoing degradation, although this figure may increase to 5.2% within a 50-year period. Approximately 67.1% of the mangroves in this region may become submerged by 2060.[7] There have been continuous mangrove conservation efforts in the countries bordering the Red Sea and the Gulf of Aden. An ambitious programme to plant 50 million mangroves in the Red Sea by 2030 has been initiated.[8] The carbon sequestration value of Red Sea mangroves has been calculated as 1,034.09 ± 180.53 megagrams of carbon per year and their potential sequestration rate as 2,424.49 ± 423.26 megagrams of carbon per year, demonstrating their potential impact with respect to addressing climate change (Blanco-Sacristán and others, 2022). The Islamic Republic of Iran hosts approximately 240 km² of mangrove forests along the Persian Gulf and the Gulf of Oman, distributed across 30 distinct habitats. This reflects a gradual increase over past decades, supported by plantation and restoration efforts, as well as the sediment accretion process, which is being increasingly influenced by climate change (Naderloo and others, 2023). Notably, over the past few decades, the Islamic Republic of Iran has successfully planted around 30 km² of mangroves and is planning to plant an additional 10 km² in the coming years, with a focus on coastal restoration and climate resilience (Naderloo and others, 2023). In addition, the country has initiated the development of a national action plan involving a broad range of stakeholders aimed at supporting effective protection, scientifically informed restoration and sustainable management of mangrove ecosystems. The mangroves in the Northern Indian Ocean are spread across South and South-East Asia. The mangroves of the Bay of Bengal in the Northern Indian Ocean are located within Bangladesh, India and Myanmar. Over the past several years, 110 km^2 of mangrove forest in the Indian part of the Sundarbans has been lost due to coastal erosion, while 81 km^2 has been gained due to plantation, ecological restoration (Ray and others, 2024) and regeneration (Samanta and others, 2021). Pollution, including anthropogenic nitrogen and microplastics, poses a long-term risk to mangroves in this region (Ghosh and others, 2022; Kumar and others, 2022). Conversions of mangroves for coastal aquaculture or for firewood have increased over the years in Bangladesh and Myanmar. In recent years, sustainable mangrove fisheries, also known as integrated mangrove aquaculture, have been implemented in coastal aquaculture ponds that were historically part of the Indian Sundarbans (Dubey, 2023; Leal and Spalding, 2024; Yash and others, 2026) (see figure II).

7 See https://iucn.org/node/33749/red-list-mangrove-ecosystems.
8 See www.redseaglobal.com.

Figure II
Pond used as a sustainable mangrove fishery (integrated mangrove aquaculture) adjacent to coastal Sundarbans, Bay of Bengal



Source: Prepared by the writing team.

The increase in erosion, along with the frequency of cyclones, poses long-term challenges to this region. Cyclone Amphan in 2020 had an impact on 1,200 km^2 of mangroves in the Bay of Bengal (Bhargava and Friess, 2020). Overall, there was a net loss in mangrove area of 3% between 1996 and 2020 (Bunting and others, 2022), despite the scarcity of data across geographical scales.

Myanmar has experienced an overall increase in mangrove cover of 0.26%, with the Ayeyarwady Region experiencing a loss of 0.95%.[9] In Thailand, more than 50% of the mangrove forests that had been lost by the 1990s have recovered as a result of conservation efforts, with an increase in total coverage of 277,923 ha (Chaiklang and others, 2024). Malaysia has lost approximately 3.3% of its mangrove cover, which fell from 650,000 ha in the 1990s to 629,038 ha in 2017 (Omar and others, 2020). Singapore, with a small mangrove forest area, has remained well managed. In the Northern Indian Ocean, aquaculture alone has accounted for 35% of mangrove loss (Leal and Spalding, 2024). Based on available data as at 2019, approximately 30% of mangrove cover has been lost in Indonesia, equating to 18,209 ha per year (Arifanti and others, 2021). According to another estimate, 637,000 ha of mangroves have been lost in Indonesia (Nurbaya and others, 2020). Deforestation poses a major threat to mangroves across the region. The conversion of mangroves for agriculture and aquaculture has led to decline (Ferreira and others, 2022). There have been regional efforts to restore mangroves, such as the National

[9] See www.un-redd.org.

Mangrove Rehabilitation Programme of Indonesia, aimed at restoring 600,000 ha of degraded mangroves by 2024 (Sasmito and others, 2023).

Between 2018 and 2023, mangroves in Australia experienced both loss, due to coastal development, and recovery. On the Great Barrier Reef, mangroves have recovered due to sustained restoration efforts. In New Zealand, mangrove cover has remained relatively stable, with some areas experiencing slight expansion due to sedimentation. It has been observed that citizen awareness and adequate protection measures have helped mangrove coverage in New Zealand. By contrast, in Papua New Guinea mangroves are facing continuous threats from logging and mining, while only a fraction have proper protection.

North Pacific Ocean

In Mexico, 44,788 ha of mangroves have been lost over the past two decades (Bunting and others, 2022; Troche-Souza and others, 2023). The main drivers of those changes have included shrimp farming and urban development. In Costa Rica, significant areas of mangrove cover that had been lost are undergoing positive change due to robust conservation practices, including the implementation of an innovative payment for ecosystem service.[10]

South Pacific Ocean

Although less well studied than the mangroves of North America, South-East Asia and Australia, the mangroves of the South Pacific Ocean cover large areas (approximately 11% of global mangrove cover) and probably represent a larger proportion of the coastline. Over the past three decades, mangrove forest cover has changed in Colombia, with the gradual transformation of dense mangrove vegetation into other vegetation types affecting an area of 38,469 ± 2,829 ha (Murillo-Sandoval and others, 2022). Mangrove cover in Colombia decreased by 48,000 ha in the three decades to 2020 (Murillo-Sandoval and others, 2022). In Ecuador, 4.56% of mangroves had been lost in previous decades, but mangroves had recovered by 2.9% by 2018 (Morocho and others, 2022). The major drivers are expanding shrimp farms, agriculture and construction activities. Fiji has lost 1,135 ha of mangroves over recent years (out of 65,243 ha) (Cameron and others, 2021). This is due to the increasing intensity of tropical cyclones. Overall management of mangrove cover in the South Pacific has remained highly complex, with a lack of effective on-the-ground assessments (Gorman, 2018).

5. Key remaining knowledge and capacity gaps

Earth observation technologies have improved significantly, but information on reduced or increased mangrove cover remains scarce (Leal and Spalding, 2024). New technologies, such as environmental DNA and machine learning, can fill in the gaps (Mandal and others, 2025), although further on-site validation is required in such regions as the Bay of Bengal and the South Pacific Ocean. Globally, mangroves also face emerging threats, such as coastal ocean acidification, with unknown consequences for carbon sequestration (Widdicombe and others, 2023). The relative rise in sea level is expected to vary across oceanic regions (Allen and others, 2018) and the responses of mangroves may vary. While mangrove loss is occurring globally, as highlighted in the second *World Ocean Assessment*, almost 50% of mangroves do not fall within the purview of the loss alert system. As countries work towards nationally determined contributions under the Paris Agreement of 2015, among others, natural climate solutions can help to achieve these targets. As part of coastal blue carbon ecosystems and natural climate solutions, mangroves can capture carbon (although this varies by region), store carbon and bring value to carbon credits (Friess and others, 2022). It should be noted, however, that knowledge gaps and uncertainties exist with respect to carbon credits and biodiversity credits, including in relation to benefit-sharing with Indigenous communities (Faridah-Hanum and others, 2018; Stankovic and others, 2023). There has been progress on limiting mangrove loss, but human activities, in particular shrimp farming and coastal development, are cumulatively magnifying the trend of reduced global coverage.

[10] See www.pewtrusts.org.

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Subchapter 5I
Salt marshes

Key points

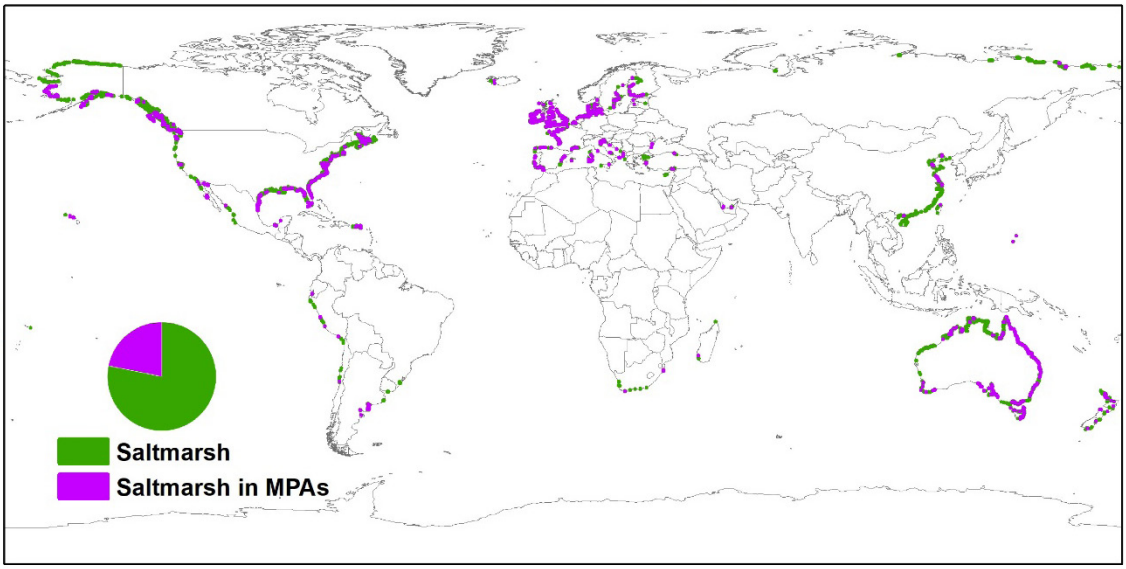
- Salt marshes are extremely valuable ecosystems that continue to be lost worldwide, due primarily to sea level rise and development.
- Techniques are being developed to restore and re-habilitate marshes; some have shown encouraging results.
- Salt marshes are also damaged by pollution and invasive species.

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1. Introduction

Salt marshes are among the most valuable ecosystems on Earth (Costanza and others, 1997), providing ecosystem services, including habitat for many species, protection from storms and flooding, "blue carbon" and nitrogen storage. They face many stressors, including sea-level rise and development, and are in global decline. Currently, only 21.8% of global salt marshes are inside marine protected areas (MPAs) (see figure I) (Mcowen and others, 2017), where human activities are restricted, with about 7.5% included in the marine world heritage sites of the United Nations Educational, Scientific and Cultural Organization (UNESCO) (Fu and others, 2024a). Worthington and others (2024) estimated their global extent in 2020 to be 52,880 km^2, distributed across 120 countries and territories, with 45% in the temperate northern Atlantic region. There have been recent reviews of their status (Armitage, 2021; Petillon and others, 2023; He and others, 2025).

Figure I
Global distribution of salt marsh ecosystems, including those in marine protected areas



Source: Data from https://habitats.oceanplus.org/, compiled by Yuan Li.

Climate change

Climate change poses the most severe threat to salt marshes worldwide. Either marsh elevation must increase at a greater rate than sea-level rise or marshes must move inland, which is possible only when there is open land behind them. In developed areas with roads and buildings, marshes cannot move inland and are subject to "coastal squeeze", eventually being submerged. Nicholls and others (1999) estimated that 1 m of sea-level rise would eliminate 46% of the world's coastal wetlands.

Rates of sea-level rise are exacerbated in regions with considerable subsidence (Ohenhen and others, 2024), increasing relative sea-level rise and reducing marshes' ability to elevate fast enough. Some marshes have inadequate sediment supply (Ensign and others, 2023) or limited potential for landward migration because of steep slopes (Thorne and others, 2018). Landward migration is further hindered by infrastructure, such as sea walls and groynes.

It has been recently realized that historical farming practices cause problems, especially when associated with sea-level rise. Straight lines of flood-tolerant *Spartina alterniflora* have appeared in the high marsh. These lines may criss-cross each other, forming a network, inside which are "waffle pools" in which water does not drain. Adamowicz and others (2020) realized that past agricultural practices of ditching and berms, combined with sea-level rise, were responsible; tidal water now floods the high marsh plants, which die and are replaced with shallow pools that expand into "megapools".

Development

Tidal wetlands have been filled for agriculture and urban development without regard for their ecological value. "Reclamation" involves dyke installation, blocking the entry of tidal water and allowing land to dry out and be developed. Stricter reclamation policies adopted in China in 2018 resulted in an increase in coastal salt marsh area of 18.7% between 2010 and 2019, and have begun to reverse a long-term net loss of 23.7% from 1985 to 2019 (Chen and others, 2022). These reductions were attributed to sea-level rise, pollution, conversion to agriculture, aquaculture, salt pans and urban development (Gu and others, 2018; Chen and others, 2022; Fu and others, 2024a). Similar losses to development are seen in Europe and America.

Bioturbation

The purple marsh crab (*Sesarma reticulatum*) causes extensive marsh damage by herbivory and bioturbation, resulting in the loss of carbon stocks in marshes along the east coast of the United States of America (Wittyngham and others, 2024). *Sesarma* "fronts" reduce elevation, causing a transition from high to low marsh (Vu and others, 2017). Martinez-Soto and Johnson (2023) found that, in the northern part of the range into which fiddler crabs expanded, *Spartina* biomass was reduced when they were present. Studies in the native range also find negative effects: Smith and Green (2015) found that fiddler crab bioturbation caused sediment loss, as excavated sediments on the surface wash away with outgoing tides. Raposa and others (2018) found negative effects of burrows near creekbanks, where erosion increased.

Protecting and rehabilitating marshes

Efforts to protect and restore salt marshes are effective in reducing decline or even increasing areal extent. Billah and others (2022) reviewed publications issued between 1990 and 2021 on restoration techniques and success indicators in North America, Europe, China and Oceania. They found that the most common techniques are recovery of tidal exchange, managed realignment, creation of marshland with dredged material and control of invasive grasses. Indicators of success included structural diversity, ecosystem functions, physical condition and species composition. They stressed that soil and plant succession functions may recover in weeks to years, while carbon storage capacity may take up to a century to recover. Raposa and others (2024) investigated whether removing upland vegetation behind marshes facilitates marsh migration. One-time removal provided little benefit; they suggested that repeated removals might be required.

Applications of thin layers of sediment over marsh (Thorne and others, 2019) can improve plant health and recruitment. As canopy density grows, sediment trapping increases and might become self-maintaining. Adequate sediment supply is essential for sustaining habitats and may promote accumulation of mineral-associated carbon (Fu and others, 2024b; Li and others, 2023). In Poplar Island, Chesapeake Bay, United States of America, where sediments had been added, Staver and others (2024) used over 10 years of data and found that elevation change in the low marsh was double the high marsh rate and exceeded the natural reference marsh and relative sea-level rise. The increase was due mostly to belowground biomass, which contributed more than surface sediment. By stimulating organic matter production and elevation change, the substrate apparently offset the low supply of sediment. Adding sediments to increase elevation is essential to long-term sustainability.

It is possible to create marshes where they previously did not exist. Stewart and others (2024) observed recession in about half of the marsh creation projects in British Columbia, Canada, representing 9.3% of the created marsh surveyed. They attributed losses to boat wake erosion and goose herbivory. Greater recession was found upriver, as was reduced dominance of native species. These remedies are much less effective than creating policies to prevent marshes being filled in for development.

Invasive species (see sect. 4, subchap. 6A)

The common reed, *Phragmites australis* (Saltonstall, 2002), arrived on the east coast of North America over a century ago and invaded many brackish and freshwater marshes. It has become a dominant species in North America, reducing plant diversity, altering patterns of water flow and causing sediment accumulation (Windham and Lathrop, 1999). It is also beneficial in sequestering contaminants (Zhang and others, 2023) and enabling marshes to increase their elevation. It is more likely to become established at low salinity and sites where rhizomes are buried in well-drained marsh areas (Bart and others, 2006). Millions of dollars are spent annually to remove it, but it inevitably returns.

Since its introduction to coastal China in the 1960s, *Spartina alterniflora* has thrived remarkably, covering

a latitudinal span of about 21 degrees from 40°47'N to 19°46'N along the coastline. By 2020, it had expanded across 519.70 km^2 (Li and others, 2022), reducing biodiversity and posing threats to artisanal fisheries and tourism (Qi and Chmura, 2023). By 2023, China had initiated nearly 200 projects to manage *S. alterniflora*, utilizing such technologies as "mowing and flooding", "mowing and ploughing" and "mowing and shading".

Salt marshes may also be damaged by non-native animals. Hogs in the marshes of the south-eastern United States reduce soil carbon storage and alter community structure (Persico and others, 2017; Hensel and others, 2021; Fischman and others, 2024). In addition to disturbing cordgrass by severing roots, creating wallows and overturning grass and soil clumps, hogs consume mussels (Hensel and others, 2021). In Ireland, the cessation of cattle grazing was associated with an increase in salt marsh invertebrate biodiversity (Lynch, 2022).

Pollution (see sect. 4, subchap. 6E)

Marsh plants take up high concentrations of toxic metals from contaminated sediments. Metals of concern include mercury, cadmium, lead and copper, which can bioaccumulate and cause toxicity. Metals in marsh sediments are affected by the presence of different plant species. Their concentrations in bare sediments were lower than vegetated "rhizosediment" in the Swartkops Estuary, South Africa (Nel and others, 2022).

Oil can have long-term effects on salt marshes once it sinks down below the surface and cannot "weather". Effects can persist decades after a spill (Culbertson and others, 2007).

Large amounts of debris accumulate in tidal wetlands and along other shorelines from both the water (such as fishing gear and abandoned boats) and the land (in the form of litter). In Brazilian marshes, Pinheiro and others (2021) found more litter in the high marsh, where the water rarely reaches, than in the middle and low marsh. Most items were plastic, from food packaging, fishery and shipping activities, and personal use. Plastics in coastal wetland sediments reach 156.7 items per kg, 200 times higher than in the water column (Ouyang and others, 2022). Variation depends on climatic and geographical zones, season, population density and waste management. Tidal wetlands contain very high concentrations of microplastics, with greater amounts in urbanized areas (Lloret and others, 2021).

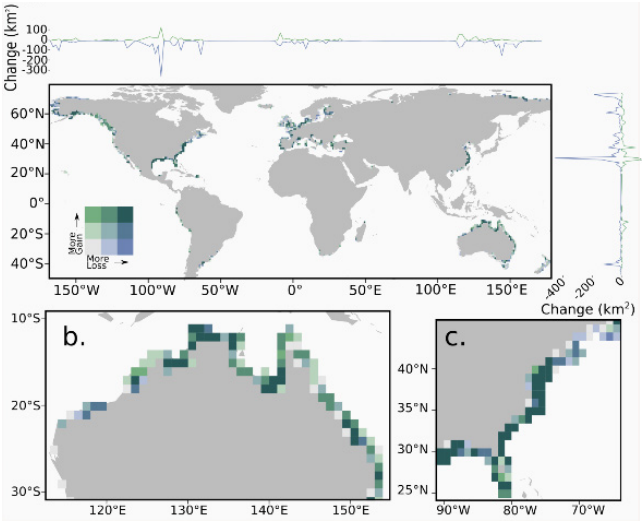
2. Environmental changes since the second *World Ocean Assessment*

Changes in overall status

Since the second *World Ocean Assessment*, marshes have continued to lose ground, though reported rates vary. In a study using satellite data conducted by the National Aeronautics and Space Administration, Campbell and others (2022) found overall global loss equivalent to two soccer (football) fields (14,280 m^2) per hour or 0.28% per year (see figure II). By contrast, a study of tidal wetlands (salt marshes, tidal flats and mangroves) found a net loss of only 4,000 km^2 over two decades (Murray and others, 2022). Coastal erosion and hurricanes accelerate marsh loss. Observed substantial reductions were primarily attributed to sea-level rise, pollution, conversion to agriculture, aquaculture, salt pans and urban development (Gu and others, 2018; Chen and others, 2022).

Figure II

Map of global salt marsh loss and gain, 2000–2019



Source: Campbell and others, 2022.

Note: (a) Global salt marsh loss and gain map in 2000–2019, visualized with a three-quantile bivariate colour ramp. Line plots of gain and loss (km^2) by longitude and latitude; (b) salt marsh gain and loss in northern Australia; (c) salt marsh gain and loss across the Atlantic coast and the Gulf of Mexico.

3. Region-specific changes

Arctic Ocean

Arctic salt marshes occur west of the Alaska Peninsula along the Bering Sea coastline and extend across the Alaskan coastal plain and the Arctic coastline of Canada. They are under pressure from climate change, coastal erosion, severe storms, changes in sea ice and increased industrial activities offshore, including oil drilling. From 2015 to 2019, there was 279.4 ± 35.9 km^2 and 5.6 ± 1.0 km^2 of salt marsh loss and gain in the Russian Federation, respectively (Campbell and others, 2022). Lack of knowledge and mapping prevents accurate quantification and leads to the underestimation of global soil organic carbon stocks, estimated at 1.44 Pg C in the top metre of tidal marsh soils globally. Ward (2020) found low-carbon stocks in salt marshes in Norway, likely due to historical isostatic uplift and sediment accretion outpacing sea-level rise.

Baltic Sea, North-East Atlantic Ocean, Mediterranean and Black Sea

Salt marsh loss is attributed mostly to reclamation. The area lost, primarily in the European region, between 2015 and 2019 was 103.2 ± 13.3 km^2, which was offset by 64.2 ± 11.3 km^2 of gain (Campbell and others, 2022).

South Atlantic Ocean and wider Caribbean

Salt marshes in South America are mostly located on the Atlantic coast, with over 95% of them in Argentina (Martinetto and others, 2023). These authors also found that these marshes store about 42.43 Mg of organic carbon per ha (40.74 below ground) and bury about 47.62 g of organic carbon per m^2 per year. In South Africa, approximately 43% of salt marsh was lost to development and agriculture between 1930 and 2018 (Adams, 2020). At their equatorial end, salt marshes are losing ground to mangroves (see sect. 4, subchap. 5H), which are moving north due to climate change (Santilan and others, 2013). Mangroves may provide increased storm protection and carbon storage (Doughty and others, 2016; Dontis and others, 2020) but may also cause a decline in habitat for some animals.

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf, Strait of Malacca and South China Sea

Salt marsh extent in India is estimated at 290 km^2 (Viswanathan and others, 2020); salt marshes are classed as ecologically sensitive areas within the Coastal Regulation Zone, with some designated as Ramsar Sites. Although salt marshes are present in the Arabian Sea (Almahasheer, 2021), there are currently no area estimates for the region.

North Pacific Ocean

Chen and others (2022) found that salt marshes in China declined from 151,324 ha in 1985 to 115,397 ha in 2019, representing a drop of 23.7%. Over the past decade, Chinese socioeconomic reforms and stricter environmental regulations have significantly decreased the contributions of anthropogenic metals in salt marshes (Fu and others, 2023). Black carbon can contribute up to 20% of the total organic carbon in salt marsh soils and, on average, 80% of this black carbon is derived from fossil fuel combustion (Li and others, 2021).

South Pacific Ocean

Salt marshes in Oceania showed a net loss of 32.1 km^2 from 2015 to 2019, primarily due to reclamation for agriculture and urban development in Australia.

Southern Ocean

Salt marshes are not found in Antarctica.

4. Key remaining knowledge and capacity gaps and new gaps

Salt marshes are being lost worldwide due to sea-level rise and continued development. There are ways to adapt to rising sea levels and preserve marshes through engineering practices (such as living shorelines and thin-layer deposition) and ways to restore or create new marshes, but legal and policy changes are needed to curtail development (Weis and others, 2021).

Roads or houses immediately upland of a marsh prevent migration and cause “coastal squeeze”. Such houses are likely to be frequently flooded; some homeowners will therefore be willing to move. In such situations, marsh migration pathways could be created, opening space for the marsh. This can be facilitated by offering incentives for residents to move away, through easements, land

acquisition, buyouts and other means, whereby people would receive compensation. Such agreements could be concluded with whole neighbourhoods; success will require efforts by planners and social workers, since people may be on low incomes, feel attached to their neighbourhoods, and want to stay despite the risks (Van Dolah and others, 2020).

As marsh edges erode, losses can be reduced by placing hard structures, such as oyster reefs or rocks, near the eroding edge, making a "living shoreline". Challenges include site-specific factors (marshes are not all the same), weather (Currin and others, 2017), performance standards (Sutton-Grier and others, 2015) and regional norms (Zhu and others, 2020; Morris and others, 2019). Living shorelines generally succeed if they can persist past their initial stages. Thin channels ("runnels") can be dug to connect pools to tidal creeks in order to drain them, provided that the creek has a lower elevation than the pool (Watson and others, 2022).

More work is needed to understand the effects of increased temperature on marsh structure and function (Duarte and others, 2021). While oil and chemical contaminants are decreasing due to environmental policies, plastic pollution continues unabated. If marshes are to continue to exist throughout this century, nations should take proactive steps to preserve and protect them. To reduce plastic waste, nations should ban single-use plastics, restrict plastic uses and ensure that the burden of disposal and recycling is borne by the plastic industry, not by Governments or individuals (Brander and others, 2024).

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Subchapter 5J
Continental slopes and submarine canyons

Key points

- Continental slopes and submarine canyons are increasingly affected by direct anthropogenic impacts and by climate change.
- Fishing, waste dumping, litter and plastic pollution, oil and gas exploration and exploitation, placement of seafloor infrastructures, noise generation and tourism appear as the human activities with the most impact.
- Submarine canyons are highly valuable biodiversity hotspots, including corals, sponges and cetaceans.
- Little is known about the capability and timescales of continental slopes and submarine canyons to recover after disturbance, but they are generally much slower compared to shallow waters. The recovery of habitats affected by bottom trawling can take decades while key ecosystem engineers rebuild.
- Despite substantial advances in slope and canyon knowledge, conservation and management, many of the gaps identified in the second *World Ocean Assessment* remain.
- Most continental slope and submarine canyon habitats remain unexplored and mid- to long-term data are limited, making it difficult to assess changes over the past 5 to 10 years.

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1. Introduction

The continental slope represents the seafloor province extending from the shelf edge (100–1,000 m depth or more) to the upper limit of the continental rise (1,000–4,000 m or more). Continental slopes vary in width, gradient and length, covering 19.6 million km^2, or 5.2% of the global ocean floor, and are often incised by submarine canyons (Anell, 2024), which are slope dissecting steep-walled valleys varying in shape, length and configuration. Canyons serve as drainage networks conveying sediments, organic matter and pollutants from shallow to deep (Canals and others, 2006; Zhong and Peng, 2021; Jones and others, 2022). Intense hydrodynamic processes may occur in canyons eventually involving different water masses. Over 10,000 submarine canyons are known, with more yet to be mapped in underexplored oceanic regions.

2. Developments in understanding of continental slopes and submarine canyons

Functioning

The continental slope is a depocenter where sedimentary and organic particles can accumulate and be buried due to a hydrodynamic regime weaker than that on the shelf (Bianchi and others, 2018; Ausín and others, 2021). Longshore hydrographic fronts and the balance between the horizontal pressure gradient and Coriolis force create major water flows along isobaths. By promoting the slow, long-term sorting and redeposition of seafloor sediments, these currents create large deposits (contourite drifts) (Thran and others, 2018; Wilckens, 2023) that can trap substantial amounts of organic carbon (Yin and others, 2024).

Submarine canyons enhance the connectivity between coastal and deep realms (Maier and others, 2019) and accelerate the transfer of material from the shelf to deep waters, which promotes carbon sequestration (Baker and others, 2024). Canyon dynamics can encompass strong and deep tidal currents, local upwelling, bringing nutrients into the euphotic zone enhancing primary production (Saldías and others, 2021; Brun and others, 2023) and deep upwelling that can contribute to global diapycnal mixing (Wynne-Cattanach and others, 2024). Canyons also channel dense waters that cascade down continental slopes, enhancing cross-margin export of matter (Luneva and others, 2020; Durrieu de Madron and others, 2023). At high latitudes, shoreward cross-isobath flows may transport warm currents to the continental shelf, thus easing the melting of sea-terminating glaciers (Wynne-Cattanach and others, 2024; Donda and others, 2024). Marine heatwaves can reach upper continental slope and submarine canyon depths (Amaya and others, 2023).

Submarine canyons are also loci for the reflection and refraction of internal waves and tides that could exceed 100 m in amplitude, leading to increased energy focusing and dissipation, resuspension and mixing (Hall and others, 2017; McPhee-Shaw and others, 2021; Tian and others, 2024), thereby affecting resident benthic communities (Pearman and others, 2023).

Episodic gravitational processes, some of which could generate tsunamis, help shape continental slopes and canyons. Land-detached canyons can be as active (Heijnen and others, 2022) as those connected to the biggest river systems on Earth (Azpiroz-Zabala and others, 2017).

Effects of climate change

Canyon inhabitants are vulnerable to climate change given they often live near their tolerance limits of temperature, aragonite saturation, oxygen concentration and nutrient levels. By 2100, significant increases in temperature with decreases in pH, dissolved oxygen and particulate organic carbon (POC) in canyons and continental slope areas are projected under the high CO_2 emissions scenario RCP8.5 especially, with atmospheric CO_2 at approximately 940 parts per million and mean global temperature of approximately 3.7°C above pre-industrial levels (Levin, 2018, 2019; Bindoff and others, 2019). However, the heterogeneous, synergistic and compounding effects of climate change-related processes will be highly variable, spatially defined and species-dependent.

Anthropogenic CO_2 has already descended to canyon intermediate water depths (Trotter and others, 2019; Fontela and others, 2020). Climate velocity models have now identified the mesopelagic zone as highly susceptible to major shifts in biogeography (Brito-Morales and others, 2020). Since corals underpin deepwater reef ecosystems and local biodiversity hotspots, large reductions in coral habitat suitability predicted by 2100

(e.g. more than 79% in the North Atlantic) will have major ecological ramifications (Morato and others, 2020) (see sect. 4, subchap. 5E). In deep waters, ingress of CO_2 via overturning ocean circulation has caused shoaling of the carbonate compensation depth; canyons in the South-West Atlantic are deemed most vulnerable where substrates below the carbonate compensation depth have doubled since pre-industrial times (Harris and others, 2023b).

The Mediterranean Sea is at the forefront of climate change, as it is warming faster than the global ocean. While invertebrate mass mortality events have occurred across the continental shelf, abrupt temperature increases and intensified oligotrophic conditions around canyons are now threatening deeper water communities (Bahamon and others, 2020). Globally, limited experimental and in-situ data show deepwater taxa are variably sensitive to warming at different life stages, thus reduced metabolic function, increased mortality and latitudinal or depth migration is expected under higher temperature conditions (Bindoff and others, 2019; Simões and others, 2021; Lang and others, 2023; Scanes and others, 2024). Together with Antarctic warming, sea-ice retreat will reduce nutrient-rich zones and biomass in canyons (FAO, 2018; Bindoff and others, 2019). Krill, a keystone species of marine food webs, have already responded by their poleward contraction (Atkinson and others, 2019; Kawaguchi and others, 2024); thus, canyons in lower latitudes may serve as future refuges for krill (Santora and others, 2018).

At oxygen minima zones (e.g. African margins), where colonial corals appear hypoxia-tolerant (Wienberg and others, 2023) (see sect. 4, subchap. 5E), greater sensitivities are expected in organisms living close to their metabolic thresholds. As these zones expand, the consequent impacts on mortality, reproduction and other physiological impairments will restructure or potentially decimate canyon and slope ecosystems.

3. Value of continental slopes and submarine canyons as biodiversity hotspots

Continental slopes and submarine canyons can be biodiversity hotspots (De Leo and Puig, 2018; Ismail and others, 2018). Compared with continental slopes, canyons feature complex and dynamic environments with higher spatial heterogeneity and a wider range of habitats and communities.

Coral and sponge hotspots

Sediment-rich continental slopes host extensive soft coral communities, like bamboo corals, sea pens and sponge grounds that provide crucial habitats for invertebrates and fish (Santín and others, 2018; Compaire and others, 2021; Grinyó and others, 2021). Highly dynamic, nutrient-rich and morphologically complex canyons support hard corals and sponges and attract fish (Corbera and others, 2019; Saunders and others, 2021; Guy and Metaxas, 2022). Recent studies of the distribution of deep-sea habitats reveal new locations of cold-water corals (Bo and others, 2023; Trotter and others, 2019, 2022), soft-corals (Long and others, 2020) and biodiversity hotspots (Moccia and others, 2019, 2021; Gayá-Vilar and others, 2024), as well as changes in priority habitats (Moura and others, 2020; Nestorowicz and others, 2021). These discoveries show how depth, relief, local hydrodynamics and substratum collectively impact habitat distribution and emphasize the need for further exploration and extensive conservation (see sect. 4, subchap. 5E).

Recent discoveries of new deep-sea species (e.g. sponges, gastropods, octocorals and corals) including 111 unique taxa off the Western Antarctic Peninsula (Friedlander and others, 2020), highlight the need for ongoing taxonomic reviews (Addamo and others, 2024) (see sect. 4, subchap. 5E).

Cetacean hotspots

Submarine canyons, due to their complex topography and enhanced nutrient cycling provide productive conditions for marine mammals, whereas continental slopes serve as important feeding grounds and corridors for migratory cetaceans (Cannaby and others, 2023; Loutrage and others, 2023; Ransier and others, 2024). Temperature and productivity influence cetacean distribution (Granata and others, 2020; Salgado Kent and others, 2021) and their higher diversity in canyons (Hodge and others, 2022), highlighting their importance for cetacean conservation. The use of species distribution models (Feyrer and others, 2024) and environmental DNA (Boldrocchi and others, 2024; Jeunen and others, 2024) has improved habitat characterization for various cetacean species along continental slopes.

4. Natural resources and ecosystem services

Continental slopes and submarine canyons sustain many supporting, provisioning, regulating and cultural services that are crucial to human well-being. These include: (i) seafood (Fanelli and others, 2018; De Leo and Puig, 2018; Clavel-Henry and others, 2020); (ii) non-renewable resources, in particular oil and gas and possibly gas hydrates and deep-sea minerals in the future (Miller and others, 2018; Weaver and Billett, 2019; Zhang and others, 2019); (iii) bioactive compounds from prokaryotes (Wang and others, 2020), fungi (Ogaki and others, 2020; Varrella and others, 2021) and invertebrates, especially octocorals and demosponges (Zhang and others, 2024); (iv) space for offshore energy and communication infrastructure (Bosch and others, 2018; Danovaro and others, 2024); (v) carbon sequestration (Graves and others, 2022); (vi) nutrient cycling (Chen and others, 2022); (vii) biodiversity enhancement (De Leo and others, 2020; Ramirez-Llodra, 2020); and (viii) ecological refuges and habitats for spawning of commercial species (Ramirez-Llodra, 2020).

High-resolution data from continental slopes and canyons have identified new functions and services, some already threatened. Fisheries have moved to deep ocean environments, with documented impacts on single species and whole ecosystems (Oberle and others, 2018; Paradis and others, 2018, 2021; Taviani and others, 2023), even if new regional regulations limit their effects, such as the total closure of 87 sensitive zones between 400 and 800 m deep in the North-East Atlantic (European Union, 2022). Increasing anthropogenic impairment of the services provided by slopes and canyons, exacerbated by climate change, has prompted research on environmental management issues (Thiele, 2019; Baker and others, 2020; Amon and others, 2022).

5. Human activities and associated impacts

Loss of seafloor integrity and associated impacts

Continental slope and canyon floor integrity refers to the maintenance of the characteristic functioning of natural ecosystem processes and spatial connectedness, including the physical structure and biotic composition of the benthic community (Rice and others, 2010). Many human activities impact the seafloor and associated communities, causing disturbance or physical loss (ICES, 2019) and compromising the provision of ecosystem services. Loss involves sealed (e.g. pipelines, cables) or unsealed (e.g. bottom trawling) disappearance of the natural seafloor, which can occur over different time intervals (Buhl-Mortensen and Buhl-Mortensen, 2018). Other harmful activities include mining of hydrothermal sulfide fields, crusts and phosphates on continental slope settings (Curric, 2016; Carver, 2019; Galley and others, 2020; Jones and others, 2020; van Putten and others, 2023). The International Seabed Authority (ISA) has discussed the draft regulations on exploitation of mineral resources in the Area — which might include continental slope settings beyond the limits of national jurisdiction — in order to ensure effective protection for the marine environment from harmful effects that may arise from such activities.

Fishing

Bottom trawling is the most significant human activity on continental margins and in canyons (Tiano and others, 2024). It disrupts benthic habitats by destroying them and resuspending and overturning sediments, with impacts far surpassing natural processes like currents, especially at greater depths (Puig and others, 2012; Schönke and others, 2022). Effects extend beyond fishing grounds, as resuspended particles spread impacts across large areas, including canyon axes (Pusceddu and others, 2014; Daly and others, 2018; Bradshaw and others, 2021).

Waste dumping

Deep submarine canyons and adjacent continental slopes used for domestic and industrial waste disposal are "out of sight, out of mind" (Vare and others, 2018; Vogt and Skei, 2018; Pierdomenico and others, 2020). Canyons near populated and industrial areas especially can become conduits for land-sourced waste (Fabri and others, 2017; Bouchoucha and others, 2019). Industrial waste can spread well beyond the initial discharge site (Fontanier and others, 2020).

Oil and gas exploration and exploitation

The oil and gas industry has continued its expansion into continental slopes (Zhang and others, 2019; Wen and others, 2023). Incidents with oil spills from drilling rigs and seabed pipelines (e.g. the Deepwater Horizon disaster) continue to pose severe environmental threats (Girard and Fisher, 2018; Kujawinski and others, 2020; Cavcic,

2023). Sediment resuspension, burial from anchoring and pipeline installation and discharges of drilling muds and produced water typically affect areas within 100 to 2,000 m (Cordes and others, 2016). Hard structures, like pipelines, can become growing substrata for organisms, which should be considered during decommissioning (Rouse and others, 2019; McLean and others, 2022).

Submarine cables

The submarine communication cable industry is growing, driven by increasing demand for content and data transmission, carrying over 95% of worldwide communications. Most new installations focus on mid and low latitudes,[1] often connecting data centre hubs rather than traditional population centres (Submarine Telecoms Forum, 2024). Power cables are mostly installed in shallow waters, with some deepwater examples mostly in the Mediterranean Sea (Ardelean and Minnebo, 2015).[2] Power cables often incorporate fibre optics for communication purposes. Cable routes in deep water are chosen to minimize environmental impact and avoid geohazard-prone areas (e.g. landslides and canyons) (Clare and others, 2023).[3] Disused cables are increasingly recovered for recycling (see the second *World Ocean Assessment*).

Noise

Human-driven underwater noise pollution modifies marine soundscapes (Bayrakci and Klingelhoefer, 2024), impacting marine organisms across various trophic levels (Duarte and others, 2021). Shipping, geophysical surveys, drilling and military sonars are major sources of this pollution. While monitoring efforts are increasing, in particular for impulsive noise sources like seismic surveys (Merchant and others, 2020), data on continuous noise from shipping are limited (Jalkanen and others, 2022).

Litter and plastic pollution

Seafloor litter accumulates in submarine canyons, being greatest near populated coastlines and tourism hotspots (Canals and others, 2021; Hernandez and others, 2022; Pierdomenico and others, 2023). These include mainly single-use plastics, microplastics and lost fishing gear, which are transported by canyon hydrodynamics (Galgani and others, 2022; Harris and others, 2023a). Plastic degrades into micro and nanoplastics, threatening marine life and ecosystems, with accumulations in deep-sea sediments and biota showing alarming increases (Fossi and others, 2018; Kane and others, 2024). The persistence timescales of litter depend on composition, with those of plastics unknown but likely longest in deep-sea environments (Ward and Reddy, 2020), posing serious concerns for canyon ecosystems (Pierdomenico and others, 2019).

Tourism

Dolphin and whale-watching along the continental margins is a booming industry that supports local economies, but it can also negatively impact marine mammals. Other wildlife species can also be affected by boat-based and in-water tourist activities (Convention on the Conservation of Migratory Species of Wild Animals (CMS) Secretariat, 2025). Boat presence, noise pollution and close encounters can disrupt the behaviour of cetaceans and other species, causing stress, altering feeding and socializing patterns, and even leading to habitat abandonment (Schuler and others, 2019; Sprogis and others, 2020). However, efforts are under way to promote more sustainable and ecologically respectful tourism practices (Amerson and Parsons, 2018; Suárez-Rojas and others, 2023) (see subsect. 5A, chap. 4). It is of the utmost importance to ensure that wildlife interactions driven by tourism are conducted sustainably (CMS Secretariat, 2025).

Recovery from disturbance

While evidence of anthropogenic impacts on continental slopes and submarine canyons is growing, little is known about the recovery of these habitats. Studying deep waters is challenging and repeat surveys at impacted sites are scarce. Habitat recovery affected by bottom trawling, for example, can take decades while key ecosystem engineers like cold-water corals and sponges (CWCS) rebuild (Huvenne and others, 2016; Clark and others, 2022; Goode and others, 2024) (see sect. 4, subchap. 5E). However, once impacts are removed and conditions are favourable, recolonization by species can occur (Strong and others, 2023).

Submarine canyons, naturally prone to disturbances (e.g. slope failures and sediment flows), offer insights into natural recovery processes. The meiofauna of the Kaikōura Canyon nearly completely recovered within four years

1 See https://subtelforum.com/submarine-cable-map/.
2 See https://cyprus-mail.com/2022/10/14/euroasia-interconnector-ready-for-construction-historic-day-president-says/.
3 www.internetsociety.org/resources/doc/2024/2024-west-africa-submarine-cable-outage-report/.

after the 2016 M_w 7.8 earthquake; nematode communities still differed from pre-earthquake conditions and complete megafauna recovery is projected to take between 4.5 and 12 years (Bigham and others, 2023, 2024).

6. Future trends and need for conservation

Most continental slope and submarine canyon habitats remain unexplored and mid- to long-term data are limited, making it difficult to assess changes over the past 5 to 10 years. Natural disturbances and those derived from human activities can have immediate and widespread effects, but recovery and shifts in these deep-sea ecosystems are generally much slower compared with shallow waters (Da Ros and others, 2019).

Evidence of climate change-induced shifts in marine species is emerging. Tropicalization of demersal megafauna along the Brazilian Meridional Margin has occurred since 2013 (Alvarez Perez and Sant'Ana, 2022). European Seas (e.g. the Mediterranean, Black and Baltic Seas) have been warming since the 1980s, leading to tropicalization and deborealization (Chust and others, 2024) and the expansion of non-indigenous species (NIS) (Galil and others, 2018, 2021). Sea pens and shrimps are expected to shift to higher latitudes, while most cold-water corals will move to lower latitudes in the Atlantic (Morato and others, 2023) (see sect. 4, subchap. 5E).

Improved waste management and recycling could reduce the amount of waste reaching coastal areas and nearby canyon heads (Willis and others, 2022; Bruemmer and others, 2023). Greater enforcement of and amendments to international agreements aim to curb marine pollution.[4]

However, debate continues over the disposal of hazardous waste like radioactive materials (Buser and others, 2020; Dabrowska and others, 2021). Conservation efforts have advanced with many continental slopes and canyons now within exclusive economic zones (EEZs) and cross-boundary agreements aiming to extend conservation efforts into international waters (Fernandez-Arcaya and others, 2017).

Despite substantial advances in slope and canyon knowledge, conservation and management, many of the gaps identified in the second *World Ocean Assessment* remain. With new technologies, coordinated funding initiatives and new regulatory frameworks, major progress is anticipated to better understand canyon processes (Demopoulos and others, 2024; Wynne-Cattanach and others, 2024), quantify ecosystem functioning and services and better predict ecosystem adaptations under climate change (Sweetman and others, 2017). Marine litter and pollution research is shifting from identifications and inventories to investigations into ecotoxicological and species behavioural effects (Bruemmer and others, 2023). The expansion and increased accessibility of new technologies (e.g. automated underwater vehicles, remotely operated vehicles) and artificial intelligence-based data analysis, together with increased time series observations (Chauvet and others, 2018), will further support evidence-based management of continental margins.

7. Knowledge and capacity-building gaps

The major imbalance in data availability and access to key observational equipment and research capacity still hampers the progress to fully understand the world's continental slopes and submarine canyons. Research efforts remain focused on only a limited number of study sites, mostly within the EEZs of developed nations. The 10 most prominent institutions in submarine canyon research are based in the United States of America, Spain, France, the Kingdom of the Netherlands and the United Kingdom of Great Britain and Northern Ireland. The most studied canyons are all along the continental margins of North America (six canyons), southern Europe (four canyons) and Taiwan Province of China (one canyon) (Matos and others, 2018). Specialized vocational and university training is closely connected to marine research, industrial development and management capabilities. While there are diverse strategies and initiatives to address these imbalances (e.g. greater access to the best universities, research centres and modern infrastructure), challenges remain (Barnhill and others, 2023; Howell and others, 2020; Roberts and others, 2023).

[4] See www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx; and www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/LDC-LC-LP.aspx.

Ocean literacy campaigns are also important for societies to understand the benefits of, and provide support to, deep-sea research, which is especially critical given the general lack of interest in protecting the deep sea (Carlesi and others, 2023), despite scientists increasingly advocating its importance (Niner and others, 2018; Da Ros and others, 2019; Fanelli and others, 2021).

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Subchapter 5K
High-latitude ice

Key points

- Loss of continental ice has accelerated from the Greenland ice sheet since the early 1990s and from the Antarctic ice sheets since the late 1990s, contributing 21.0 mm to global sea-level rise from 1992 to 2020.
- Arctic sea ice will continue to decline in the future, leading to model predictions of occurrences of an ice-free Arctic Ocean during Septembers by mid-twenty-first century.
- The abrupt reduction in Antarctic sea ice extent and duration since 2016 may herald a fundamental change in the Southern Ocean.

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1. Introduction

The present subchapter focuses on two key components of Earth's climate system – sea ice and ice sheets – and how they respond to climate change. It highlights the substantial changes occurring in high-latitude cryospheres of both polar regions and their influences on the ocean and atmosphere, in particular physical impacts, as biological impacts were treated previously (United Nations, 2022a, 2022b). Sea ice forms from freezing seawater as the ocean cools each autumn and winter. Ice sheets, on the other hand, comprise glacial ice formed from snow accumulation over thousands of years which compacts and flows seawards under gravity. The mass loss from ice sheets injects large volumes of freshwater into the ocean and contributes to sea-level rise. Sea ice and ice sheets profoundly influence – and are strongly impacted by – the ocean and the atmosphere.

Interactions of the polar cryosphere with the ocean and atmosphere impact global circulation and lower-latitude atmospheric patterns and influence global weather and climate, the ocean's freshwater budget, the uptake of anthropogenic heat and carbon and global sea-level rise. Similarly, polar systems are influenced by atmospheric teleconnections to lower-latitudes and ocean variability there. At the same time, changes in the extent, mass, formation and melt, thickness and properties of polar ice can accelerate change via complex feedback processes (Goosse and others, 2018). As a thin veneer that lies between the ocean and atmosphere, sea ice reacts to change and variability in weather patterns and climate drivers at sub-daily, seasonal and decadal timescales. In contrast, the Antarctic and Greenland ice sheets respond over centuries to millenniums, although more rapid changes are beginning to occur. In short, ice sheets and sea ice are both sensitive indicators and influencers of climate change and variability via highly coupled ocean-atmosphere-cryosphere processes.

2. Arctic and Antarctic sea-ice systems

Similarities and contrasts

Sea ice includes pack ice that is in constant motion due to winds and ocean currents and fast ice that is attached to coastal margins. Each year, Earth's high-latitude oceans are transformed by the advance and retreat of sea ice driven by seasonal changes in ocean and atmosphere temperatures, wind patterns and solar insolation. In the Arctic, sea-ice extent varies between approximately 15×10^6 km^2 in March to approximately 6×10^6 km^2 in September (figure I). The lowest Arctic sea-ice extent since the start of the satellite record in 1979 occurred in September 2012 (3.39×10^6 km^2). In contrast, Antarctic sea-ice extent varies between approximately 19×10^6 km^2 in September to approximately 3×10^6 km^2 in February (figure II), with the lowest summer minimum on record being in 2023 (1.79×10^6 km^2). Sea ice greatly influences biological processes in both polar systems by impacting light, nutrients and food availability and by forming habitats for the diverse biota (United Nations, 2017, 2022a).

There are distinct differences between the two polar sea-ice systems due to differences in their geographical settings, processes of sea-ice formation and decay and ice-ocean-atmosphere interactions (Turner and Overland, 2009; Maksym, 2019). Arctic sea ice largely forms within the Arctic Ocean basin and is constrained by adjacent land masses (although sea ice in the Bering and East Greenland Seas is unconstrained). Large-scale sea-ice motion is dominated by an atmospheric high-pressure system in the western Arctic, the oceanic Transpolar Drift Stream in the central Arctic and the Beaufort Gyre, the first two of which export sea ice into the North Atlantic through the Fram Strait.

In contrast, Antarctic sea ice seasonally expands outwards from (then retreats back to) the Antarctic continent, thereby buffering (then exposing) the coastal margins of the Antarctic Ice Sheet (Reid and Massom, 2022). In winter, Antarctic sea ice extends to lower latitudes compared to the Arctic, while continually being exposed to the high winds and waves of the Southern Ocean (Massom and Stammerjohn, 2010). The overall configuration and motion of the Antarctic sea ice reflect large-scale patterns of atmospheric and ocean circulation (Holland and Kwok, 2012). Regional variations in these factors combine to create variations in timings of annual ice-edge advance, retreat, annual duration and maximum and minimum sea-ice extent (Stammerjohn and others, 2008). Antarctic sea-ice extent displays high variability over temporal scales of days to weeks due to changing winds and temperatures associated with the passage of cyclones (Uotila and others, 2011). On seasonal and inter-annual timescales, sea-ice extent and the timings of sea-ice advance and retreat

are influenced by modes of climate variability such as the El Niño/Southern Oscillation (Stammerjohn and others, 2008) and the Southern Annular Mode, the latter being a function of the surface pressure gradient between Antarctica and mid-latitudes (Marshall, 2003).

Figure I
Seasonal mean sea-ice extent in the Arctic and its variability

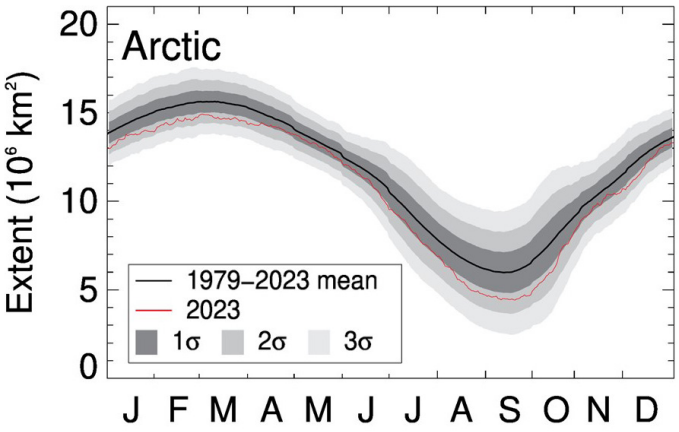
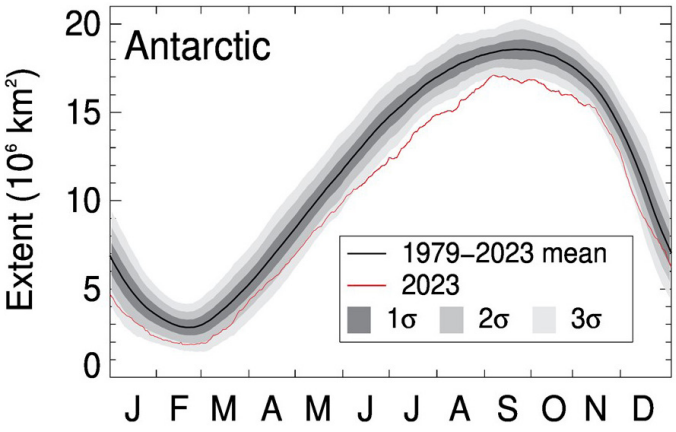


Figure II
Seasonal mean sea-ice extent in the Antarctic and its variability



Source: National Oceanic and Atmospheric Administration/National Snow and Ice Data Center, Climate Data Record of Passive Microwave Sea Ice Concentration, v.4.

Note: Mean (black line) calculated from data between 1979 and 2023; grey areas represent 1, 2 and 3 standard deviations (σ) around the mean for the same period; also shown are the data from 2023 to illustrate recent changes.

Sea-ice thickness strongly influences the heat and freshwater budgets of both polar oceans (Maksym and others, 2012). Historically, Arctic sea ice was substantially thicker, with maximum thickness reaching 6 m. In recent years much of the multi-year ice has disappeared and Arctic sea ice is now 1–2 m thick (Kwok, 2018) and largely first-year ice, thus being similar to the typical approximately 1-m thick Antarctic first-year ice (Worby and others, 1998). Fast ice is confined to narrow coastal bands ranging from a few kilometres to hundreds of kilometres wide in both the Antarctic and Arctic – depending on coastal configuration and bathymetry and the distribution of grounded icebergs – and can be annual or perennial (Mahoney, 2018; Fraser and others, 2021).

There are also differences in the oceanic settings of the two polar systems. Arctic water columns are strongly stratified, with low-salinity water at the surface underlain by a cold, salty halocline that insulates the sea ice from the warm, deeper Atlantic Water (Steele and Boyd, 1998). In the Antarctic, the upper water column is substantially saltier (although freshening in recent years) (United Nations, 2022a), allowing mixing to greater depths and a strong upward transfer of heat from warm circumpolar deep water that limits the thermodynamic growth of Antarctic sea ice to approximately 70 cm (Martinson, 1990). Only during summer does the surface of the Southern Ocean become seasonally stratified by sea-ice melt (Haumann and others, 2016).

Due to its high reflectance and low thermal conductivity, snow that accumulates on sea ice substantially modifies the physical and optical properties and growth/melt rates of the ice and its interactions with the ocean and atmosphere (Sturm and Massom, 2017). Snow depths on sea ice tend to be greater in the Antarctic than in the Arctic due to higher precipitation over the Southern Ocean (Webster and others, 2018). Sea ice also seasonally limits solar heating of the upper ocean and also acts as an insulating barrier between the ocean and atmosphere that reduces exchanges of heat and gases (e.g. water vapour, carbon dioxide (CO_2)), as well as vertical mixing of the upper ocean. Seasonal sea-ice formation and decay releases vast volumes of brine and freshwater in winter and/or summer, respectively (Meredith and Brandon, 2017). In coastal regions in the Weddell Sea, Ross Sea, parts of East Antarctica and in the Labrador and Greenland Seas, particularly high rates of sea-ice formation generate large volumes of dense brine, which sink to form bottom waters that drive the global thermohaline circulation (Abernathey and others, 2016).

Greenland and Antarctic ice sheets

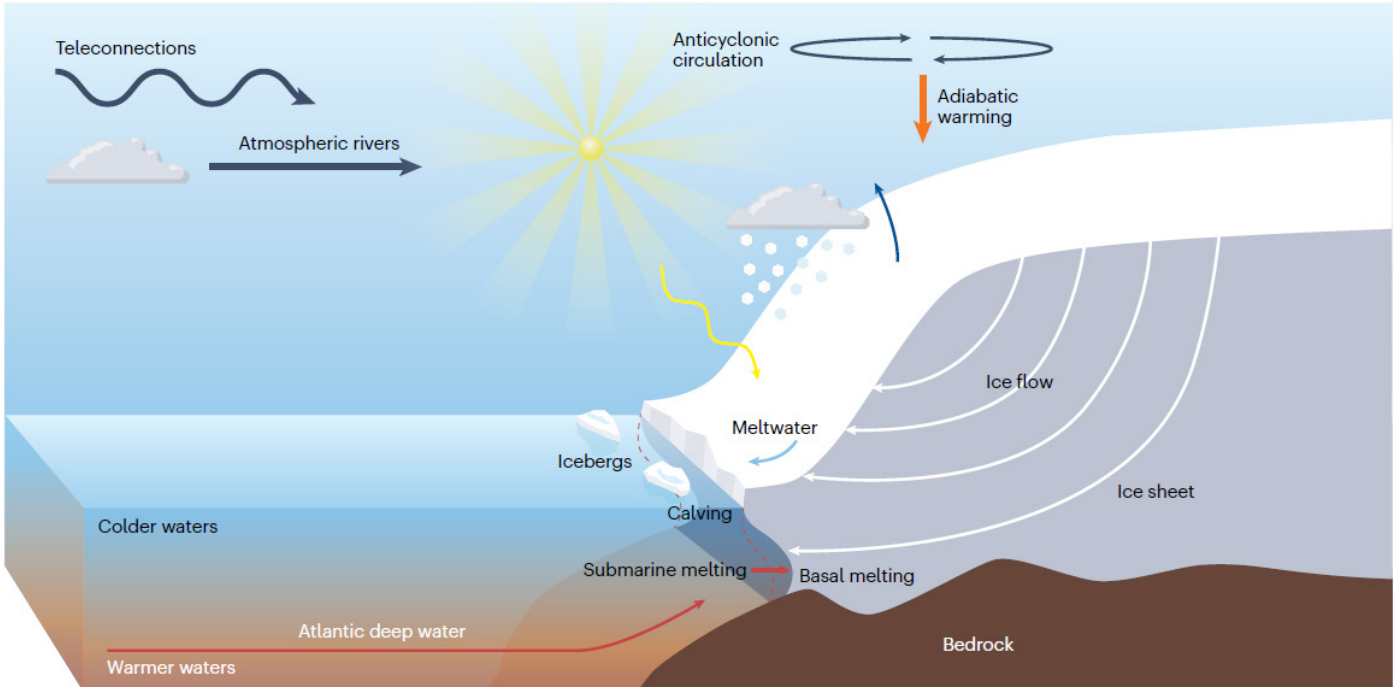
Continent-wide estimates of ice-sheet mass budgets for both Greenland and Antarctica have been completed (Otosaka and others, 2023). The Greenland and Antarctic ice sheets together store approximately 68% of Earth's freshwater. The Greenland ice sheet is approximately

1.7×10^6 km^2 in area, has a mean thickness of 1.67 km and contains 2.9×10^6 km^3 of ice (equivalent to a 7.4 m rise in sea level if completely melted; Kulp and Strauss, 2019). It lies on bedrock above sea level and drains into fjords through outlet glaciers. The Antarctic ice sheet covers approximately 14×10^6 km^2, has a mean thickness of 2.16 km and contains 26.9×10^6 km^3 of ice (Fretwell and others, 2013), enough to raise sea level by 58 m if melted. The Antarctic ice sheet has three components: the West and East Antarctic ice sheets and the Antarctic Peninsula. Unlike the Greenland ice sheet and much of the East Antarctic ice sheet, a large portion of the West Antarctic ice sheet rests on bedrock that is below sea level and more vulnerable to climate change than ice-sheet areas that are grounded above sea level. The East Antarctic ice sheet is substantially higher and thicker than the West Antarctic ice sheet (Morlighem and others, 2017) and its response to climate warming represents the largest unknown in projections of future sea-level rise (IPCC, 2023).

Ice sheets affect the ocean by releasing large volumes of freshwater through four processes (Straneo and others, 2019):

- Surface meltwater run-off (extensive across Greenland and the Antarctic Peninsula in summer)
- Discharge of sub-glacial meltwater (largely occurs in Greenland; see figure III)
- Basal melting of floating ice shelves through their contact with warm waters (predominantly for Antarctic ice shelves; see figure IV)
- Iceberg calving.

Figure III
Processes responsible for changes in ice in the Greenland ice sheet

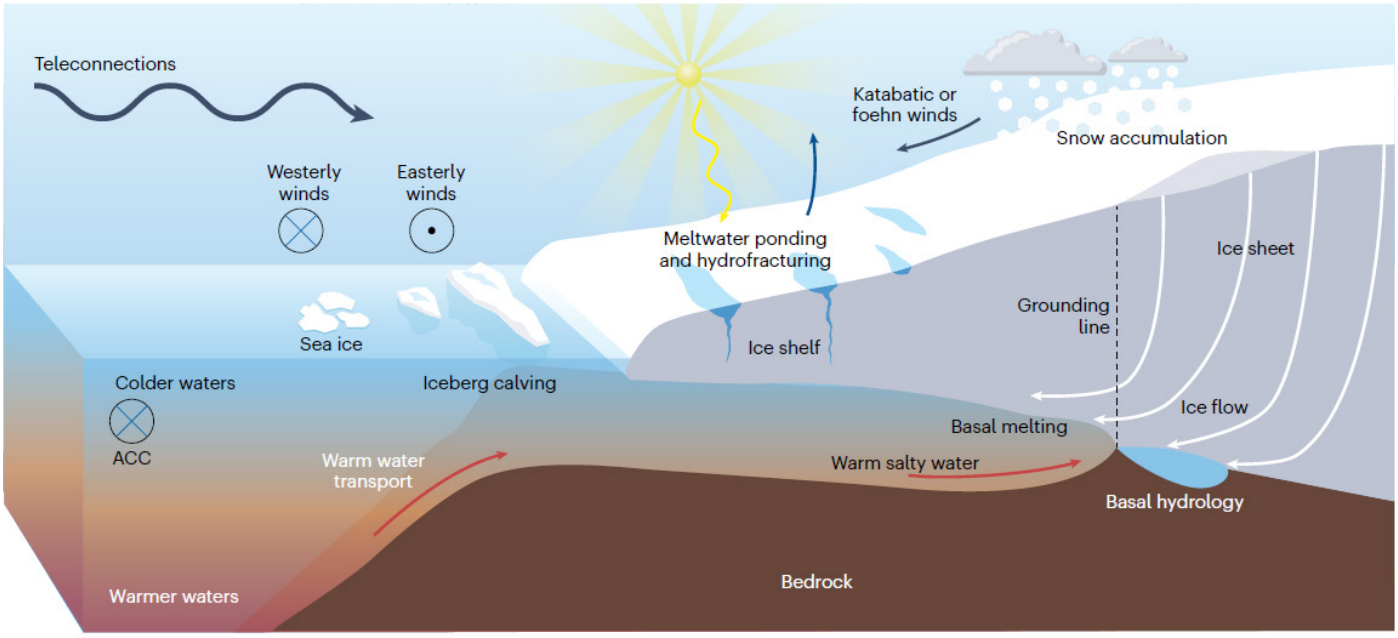


Source: Hanna and others, 2024.

Icebergs

Calving, the process by which ice mechanically fractures to form icebergs, is a natural and continuous process in the evolution of ice shelves and marine-terminating glaciers and has been estimated to account for half of the ice lost annually from both the Antarctic ice sheet (Depoorter and others, 2013) and the Greenland ice sheet (Shiggins and others, 2023). Icebergs drift large distances, or ground on shallow banks where they reside for multiple years and influence coastal sea-ice processes (polynya and fast-ice formation) and in particular conditions around Antarctica (Barber and Massom, 2007). The Antarctic ice sheet, with its seaward margin of numerous floating ice shelves and ice tongues, produces vast numbers of icebergs that vary greatly in size, with the largest tabular iceberg being over 10,000 km^2 (Budge and Long, 2018). Greenland icebergs are typically small, with dimensions similar to the thickness of the source glacier front (Reeh and others, 2001).

Figure IV
Processes responsible for changes in ice in Antarctic ice sheets



Source: Hanna and others, 2024.

3. Change and variability in the Arctic Ocean cryosphere system

Arctic sea ice

The response of Arctic sea ice to climate change has been dramatic (all sea-ice data are available from the National Snow and Ice Data Center Sea Ice Index and the European Space Agency Climate Change Initiative; see figure V). The current high rate of Arctic sea-ice loss and associated surface-ocean warming is unprecedented in the past 1,500 years (Osborne and others, 2017). Annual sea-ice extent has declined since 1979 (the start of the satellite record) but slowed since 2007, with losses being greatest in the East Siberian, Chukchi, Laptev, Barents and Kara Seas (Jahn and others, 2024). The September reduction in sea-ice extent is greatest in the Beaufort and Chukchi Seas, but the greatest March reduction has been in the Greenland and Barents Seas. The Arctic sea-ice extent summer reduction has increased open-water duration and reduced sea-ice age (Kwok, 2018) and thickness (Petty and others, 2023). Prior to 1970, multi-year ice covered most of the Arctic Ocean (i.e. approximately 5.5×10^6 km^2 in winter). Thereafter, the multi-year ice area decreased to a minimum of 1.6×10^6 km^2 in 2017 (Kwok, 2018) and now the Arctic is largely covered by thinner first-year ice that is more vulnerable to seasonal melt (Stroeve and Notz, 2018). Climate models project a continued decline, resulting in an ice-free[1] end of summer Arctic Ocean by 2050 (Kim and others, 2023; Jahn and others, 2024).

Greenland ice sheet

The mass loss of the Greenland ice sheet is the second-largest contributor to sea-level rise after ocean thermal expansion (Zemp and others, 2019), contributing approximately 14 ± 2 mm between 1992 and 2020 at a loss rate of 169 gigatons per year, representing a 645% increase relative to its historical contribution (from 1992 to 1996) (Otosaka and others, 2023). The enhanced loss of ice from the Greenland ice sheet results from changes in atmospheric and oceanic forcing that drive increases in surface and submarine melting and calving (Hanna and others, 2024).

[1] The term "ice-free" used here should not be confused with a formal navigational term "ice-free" of the relevant United Nations bodies (World Meteorological Organization, International Maritime Organization). As icebergs will continue to be present within the domains of the Arctic and Southern Oceans, the term "ice-free" navigationally is not applicable.

Figure V
Annual Arctic sea-ice extent since 1979

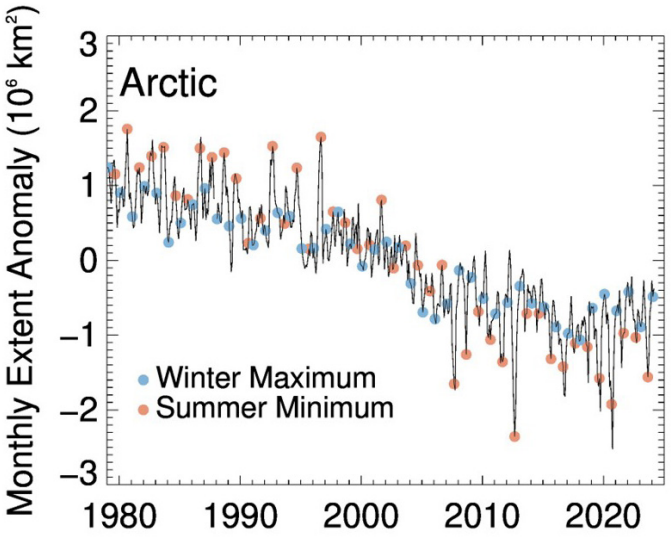
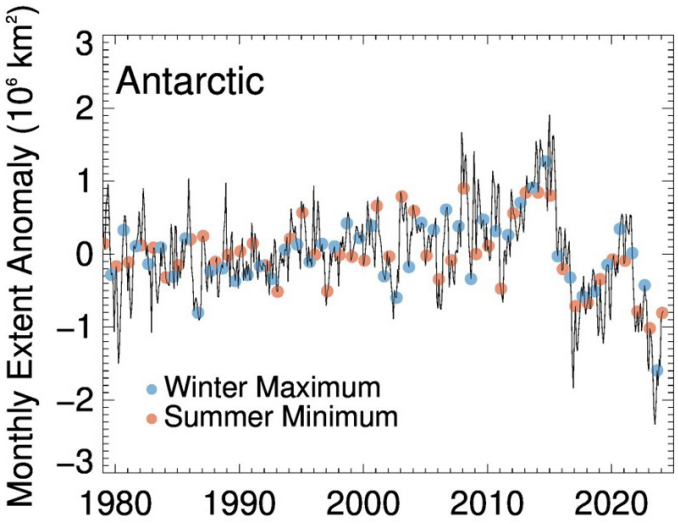


Figure VI
Annual Antarctic sea-ice extent since 1979



Source: National Oceanic and Atmospheric Administration/National Snow and Ice Data Center, Climate Data Record of Passive Microwave Sea Ice Concentration, v.4.

4. Change and variability in the Antarctic Ocean cryosphere system

Southern Ocean sea ice

The circumpolar average of Antarctic sea-ice extent increased slightly between 1979 and 2015, reaching consecutive record-high winter sea-ice extents in 2012, 2013 and 2014, but then decreased substantially in 2016, reaching consecutive record-low summer sea-ice extents in 2017, 2022, 2023 and 2024. Extreme record-low winter sea-ice extent occurred in 2023 and 2024. Since the winter of 2015, seasonal sea-ice extent has remained largely below the mean from 1979 to 2024 (figure VI), potentially heralding a regime shift in the Southern Ocean (Hobbs and others, 2024). An observed shift to longer persistence of sea-ice anomalies, changed response to atmospheric forcing and increases in the spatial coherence of anomalies (Hobbs and others, 2024; Schroeter and others, 2023) could indicate a fundamental change in the highly coupled sea ice–ocean–atmosphere system (Eayrs and others, 2021; Raphael and Handcock 2022; Purich and Doddridge, 2023).

Antarctic ice sheet

Between 1992 and 2020, the Antarctic ice sheet lost 2,671 gigatons of ice, equivalent to 7.4 mm of sea-level rise or nearly half of the Greenland ice-sheet contribution. Antarctica's contribution to sea-level rise increased from 0.14 mm per year between 1992 and 1999 to 0.39 mm per year from 2010 to 2020 (Otosaka and others, 2023). Most of this loss has come from the West Antarctic ice sheet, where major outlet glaciers (Pine Island and Thwaites) have undergone enhanced melting, thinning and retreat leading to increased discharge of grounded ice (Jenkins and others, 2018). The Antarctic Peninsula has shed 13 gigatons/year, while East Antarctica remains near equilibrium. East Antarctica, however, constitutes the most uncertain component in future predictions of Antarctica's contribution to sea-level rise (Fricker and others, 2025).

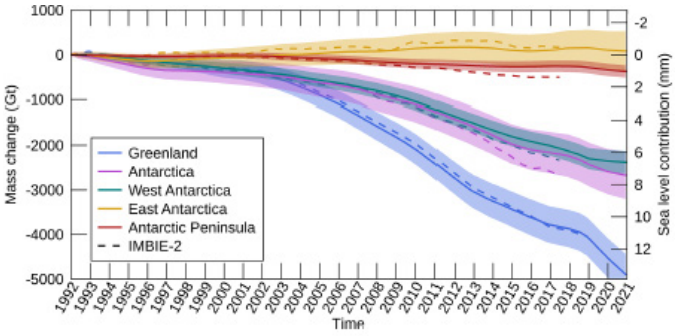
Antarctic ice shelves

Of paramount importance to the Antarctic ice sheet-ocean system is the structural integrity of ice shelves, which are far less common around the Greenland ice sheet (Bindschadler and others, 2011). Ice shelves play a crucial role in moderating the ice sheet's contribution to sea-level rise by buttressing the discharge of grounded ice mass into the ocean, yet they are the most vulnerable part of the ice-sheet system, with recent extensive thinning due to basal melting by the increased presence of warm ocean waters within ice-shelf cavities (Verfaillie and others, 2022). Moreover, abrupt ice-shelf mechanical disintegration has occurred, caused by thinning, melting and increased exposure to wave forcing along ice-shelf fronts (e.g. on the Antarctic Peninsula) (Massom and

others, 2018; figure VII). Rates of basal melting and calving vary regionally (Hanna and others, 2024) and are impacted by atmospheric and oceanic forcing. Iceberg calving is the largest factor affecting ice-shelf area, whereas ice-front retreat and thinning are secondary factors (Greene and others, 2024). Large calving events (e.g. tabular iceberg B15) can disrupt Antarctic Bottom Water formation by decreasing sea-ice production in coastal polynyas (areas of vigorous ice production driven by persistent off-ice winds; Tamura and others, 2012). In addition, glacial meltwater inputs and ocean freshening can affect sea-ice production and in certain areas (e.g. the Ross Sea) can also influence Antarctic Bottom Water production (Jacobs and Giulivi, 2010). There is substantial concern that various ice-shelf and glacial response processes could lead to rapid ice loss (characterized by the IPCC (2023) as a low-likelihood, high-impact scenario for high rates of sea-level rise), but the mechanisms for such collapse are uncertain (e.g. Sergienko, 2022; Morlighem and others, 2024).

Figure VII

Cumulative ice-sheet mass changes for ice sheets in Greenland and Antarctica



Source: Otosaka and others, 2023.

Note: Shaded areas represent the associated uncertainties and are calculated according to Otosaka and others (2023) and dashed lines show the results from the IMBIE Team (2020).

5. Outlook

Under the current emission rates of greenhouse gases, ice coverage and volume will continue to decrease and the impacts of this reduction will increase markedly (Chown and others, 2022). With increased open water in both polar regions and the loss of a protective sea-ice buffer, erosion of coastal margins will accelerate due to predicted increased storms and wave heights. Increased ice discharge from ice sheets will result in a heightened sea level, endangering coastal communities globally. Increased shipping and other human activities (e.g. tourism) in both regions will produce disturbance and release of pollutants, endangering regional biota. Loss of sea ice in both regions also has the potential to accentuate climate warming via complex feedback mechanisms (Goosse and others, 2018), which further accelerate ice loss.

6. Key remaining knowledge and capacity gaps

While significant advances have been made to understand processes driving cryospheric change in polar regions, further progress is urgently needed, given the global impacts of ice loss and the fact that climate models cannot as yet reliably predict future changes and their impacts. Specific gaps include:

- Understanding the recent abrupt declines in Antarctic sea ice (in particular those in autumn-winter) and potential future changes
- Quantifying the thickness distributions of Antarctic sea ice and its snow cover and determining whether these are changing
- Understanding subglacial processes under polar ice sheets that control ice discharge into surrounding oceans
- Understanding processes such as supraglacial and subglacial hydrology and iceberg calving mechanisms
- Quantifying processes impacting sea-level rise
- Reducing uncertainty in the timing of an open-water Arctic.

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Subchapter 5L
Seamounts and pinnacles

Key points

- There has been an increase in:
  - Seamount studies using novel and integrated approaches such as environmental DNA, camera systems, human-occupied or remotely operated vehicles, baited remote underwater videos and machine learning.
  - Seamount pressures and impacts, including fishing, mining interests, ocean acidification and climate change effects.
  - Protection legislation.
- While most studies in the global ocean report a seamount effect on the physical oceanographic environment and biological processes, a few found conflicting results when seamounts are studied on a case-by-case basis.
- Despite significant improvements, the understanding of abyssal seamounts, those found within areas beyond national jurisdictions and connectivity of seamount fauna remains limited.

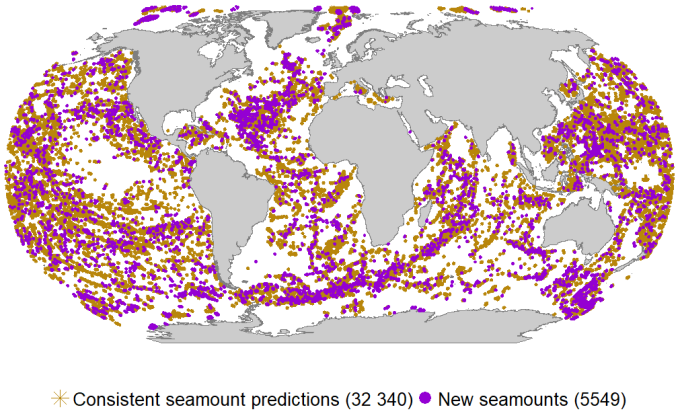
Writing team: Pavanee Annasawmy (coordinating author), Amy R. Baco, Malcolm R. Clark, Réka Domokos, Dannielle Eager, Jason M. Hall-Spencer, Astrid Leitner, Ariadna Mecho, Yutaka Michida (lead member), Telmo Morato, Jose Angel Alvarez Perez, Roberto de Pinho (co-lead member), Yeqiang Shu and Junlong Zhang.

1. Introduction

Seamounts are underwater topographic features that rise at least 1,000 m from the seabed, with small pillar-like features termed pinnacles (Leitner and others, 2021a). The number of predicted seamount locations has increased due to heightened interest and technical advances (see figure I; Yesson and others, 2021; Gevorgian and others, 2023).

The present subchapter reviews a non-exhaustive list of advancements in understanding seamount distributions, related physical processes, ecological patterns and pressures, highlighting region-specific changes (supplementary tables 1–8 accessible here: https://doi.org/10.13140/RG.2.2.35490.08647). The subchapter does not include detailed scientific definitions or explanations.

Figure I
Seamount predictions



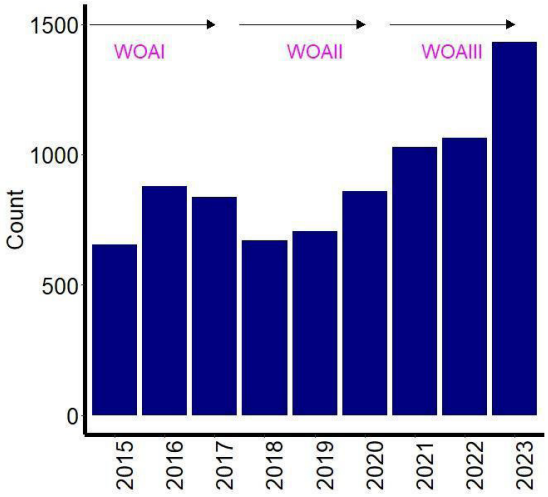
Source: Adapted from Yesson and others, 2021 (credit: Pavanee Annasawmy).

2. Description of changes in knowledge since the first *World Ocean Assessment*

Since the publication of the first *World Ocean Assessment*, there has been an increase in seamount publications following reanalysis of archived data and recent multidisciplinary surveys (see figure II), likely driven by increasing interest in exploration, species distribution and ecology for sustainable fisheries and conservation, human impacts and the role of seamounts in the global carbon pump and sink (Tao and others, 2022).

The following key differences are noted between the second and third World Ocean Assessments (see table).

Figure II
Increase in seamount literature since the publication of the first *World Ocean Assessment*



Source: https://doi.org/10.13140/RG.2.2.32056.00000 (accessed 14 June 2024; credit: Pavanee Annasawmy).

Table
Brief advances in seamount knowledge since the second *World Ocean Assessment*

Knowledge baseline (second *World Ocean Assessment*)	Progress in knowledge (third *World Ocean Assessment*)
Limited seamount sampling	Enhanced sampling via multidisciplinary cruises, novel approaches, autonomous platforms and improved seamount detection algorithms
Generalized seamount "ecological paradigms"	Paradigms questioned through case-by-case studies
Few region-specific studies noted, especially in the Arctic, Southern and Indian Oceans	Increased research in these regions
Climate change effects limited to oxygen concentration decline	Additional effects on trophic connections and species distributions
Few working groups limited to the global North on seamount conservation and management	Seamount working group established in the Indian Ocean
Limited seamount legislation	Expanding seamount legislation

Source: Prepared by the writing team.

3. Region-specific changes

Global studies provided high-resolution habitat suitability models for deep-sea reef-forming hard corals, few soft coral species and thorn/black corals (Yesson and others, 2017; Cordes and others, 2023; Tong and others, 2023).

Region-specific changes are summarized below and described in detail in the supplementary tables.

Arctic

Similar to the reporting period for the second *World Ocean Assessment*, recent research on Arctic seamounts (see figure III and supplementary table 1) focused on sediments and sponge communities, yielding the following key findings: sponge-dominated communities on the Schulz Bank vary by depth and the type of substrata (Meyer and others, 2023); the sedimentary cover on Mosby seamount dates from the middle Miocene or younger (Geissler and others, 2019); on Langseth Ridge, sponge life is associated with extinct seep life (von Jackwoski and others, 2023) and sponges play a role in pelagic-benthic coupling of microbial communities (Morganti and others, 2022); megafaunal densities and assemblage composition vary between seamounts of the Langseth Ridge (Stratmann and others, 2022).

South Atlantic and wider Caribbean

Vulnerable marine ecosystems are groups of species, communities or habitats that may be vulnerable to impacts from fishing activities (FAO, 2025). Areas hosting certain categories of organisms that may be classified as indicator species, such as seamounts, may be considered vulnerable marine ecosystems with subsequent management measures such as designations of marine protected areas (MPAs) to conserve those ecosystem attributes (Watling and Auster, 2021; Vinha and others, 2024). Deep-sea corals and sponges act as indicator species for vulnerable marine ecosystems (Watling and Auster, 2020).

Figure III
Location of few Arctic seamounts

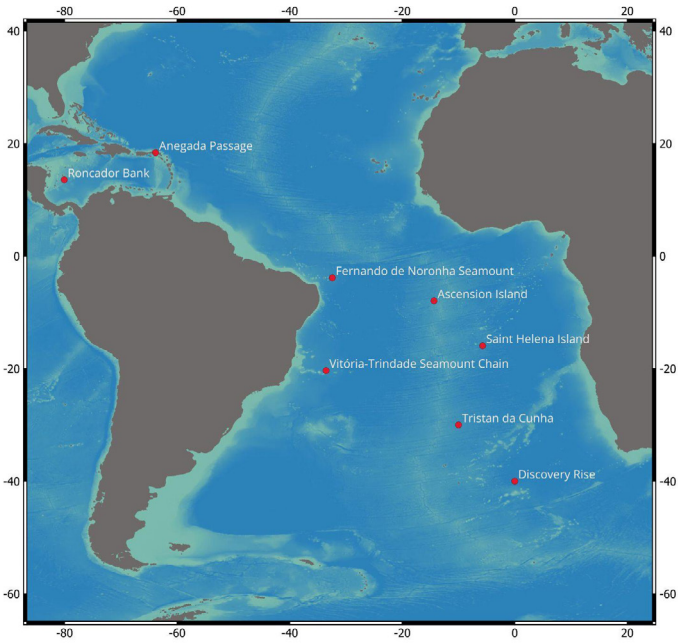


Source: Pavanee Annasawmy.

Seamounts of the Discovery Rise were explored by an international effort to map vulnerable marine ecosystems (see figure IV and supplementary table 2). Cold-water

coral communities (scleractinians and gorgonians), 36 fish morphotypes (*Laemonema* sp., *Guttigadus* sp.) and 13 cephalopod flank/summit residents, classified in five morphotypes (*Moroteuthopsis ingens*, *Histioteuthis* cf. *atlantica*, *Opisthoteuthis* cf. *agassizii*) were uncovered. These records supported the maintenance of fishing closure areas within the South East Atlantic Fisheries Organisation Convention Area (Perez and others, 2022).

Figure IV
Location of South Atlantic seamounts, islands and other features



Source: Ariadna Mecho.

Genetic connectivity of seamount populations of Bluenose Warehou (*Hyperoglyphe antarctica*) was reported between four seamounts within the Tristan da Cunha exclusive economic zone (EEZ) (Heyworth and others, 2021). Latitude and depth were drivers of benthic assemblage composition, differentiating the 13 tropical and temperate seamounts and oceanic islands of Ascension, Saint Helena and Tristan da Cunha (Bridges and others, 2021). Seamounts were hotspots for fishes living below 200 m depth and micronekton (crustaceans, fishes and cephalopods of 2 to 20 cm in size) over summits less than 200 m (Campanella and others, 2021). Vulnerable marine ecosystems were described and protected within the boundaries of MPAs established in the Tristan da Cunha EEZ.

The Fernando de Noronha and the Vitória-Trindade seamount chains and underlying currents drive the genetic diversity of *Octopus insularis* (Lima and others, 2022).

Further research showed species connectivity between seamounts of the Fernando de Noronha Ridge (Tosetto and others, 2024), seismic activities at Roncador bank (Idárraga-García and León, 2019) and factors influencing coral assemblage and communities at Anegada passage (Quattrini and others, 2017; Auscavitch and others, 2020).

North Atlantic

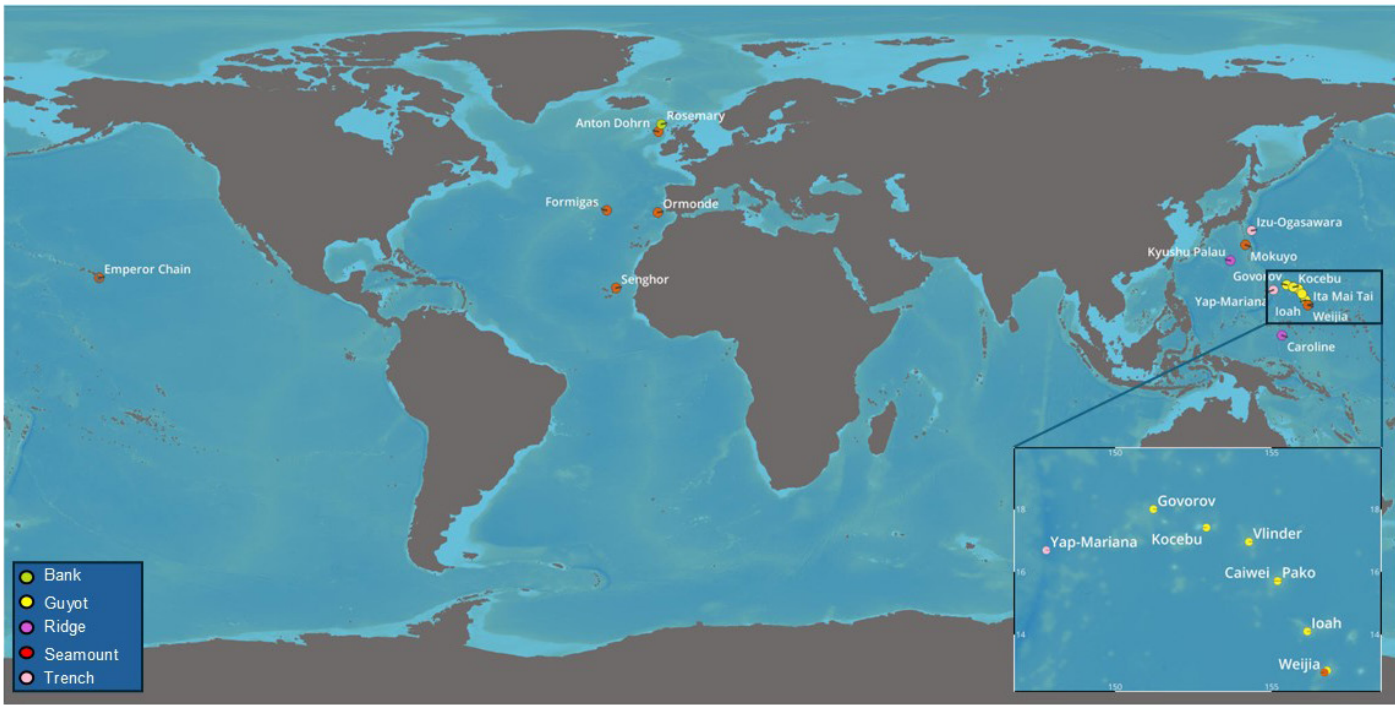
North Atlantic seamounts (see figure V and supplementary table 3) were investigated during recent expeditions by Germany and the United States of America. A science-based and participatory process shepherded by the regional government led to the creation of the largest MPA network (Azores Marine Protected Area Network; 287,000 km^2) in Europe, 15% designated as fully protected and 15% as highly protected. Positive effects of the Azores MPA archipelago were observed on resident, large-bodied fishes and higher fish abundance in deeper habitats (Afonso and others, 2018). The dynamic interactions between hydrology and seamount topography support enhanced food supply and presence of vulnerable marine ecosystems taxa at Cabo Verde seamounts (Vinha and others, 2024). Internal waves influenced local hydrology, potentially driving food and nutrient supply and contributing to larval fish aggregations and higher trophic level predators at Senghor seamount (Denda and others, 2017; Mohn and others, 2021), coral larvae dispersal at Rosemary seamount (Stashchuk and Vlasenko, 2021) and supported benthic communities at Ormonde and Formigas seamount (Mosquera Giménez and others, 2019).

North Pacific

North West, Central and North East Pacific seamounts and pinnacles (see figure V) remain the most studied ones in the world's ocean. Recent studies by Canada, China, the Russian Federation and the United States of America and the use of autonomous and mobile technologies (useful for providing longer time series, allowing the mapping of seafloor habitats, greater sampling collection and refined observations through real-time video footage), as well as machine learning (enhancing data processing and analyses), have enhanced the understanding of the formation and evolution, biodiversity and taxonomy, biogeochemistry, seamount effect on the physical oceanographic environment (e.g. presence of anticyclonic caps, taylor columns, internal waves) impacting all trophic levels, from microbes to megafauna and ecosystem research and management of these

seamounts (Baco and others, 2017, 2023b; Domokos, 2022; Mejia-Mercado and Baco, 2022, 2023; Leitner and others, 2021a, 2021b, 2021c; Shu and others, 2022; Wang and others, 2024; supplementary table 4). Time series of the Mokuyo, Izu-Ogasawara Arc have shown shifts in vent communities (Chen and others, 2024).

Figure V
Location of North Atlantic and Pacific bathymetric features



Source: Ariadna Mecho.

Ecologically or biologically significant marine areas are areas that hold special importance in terms of their ecological and biological characteristics (e.g. by providing essential habitats, food sources or breeding grounds for particular species). Seamounts of the North-West Pacific in areas beyond national jurisdictions qualify as ecologically or biologically significant marine areas amid existing or anticipated pressures linked to potential seabed mining and climate change (Du Preez and others, 2023).

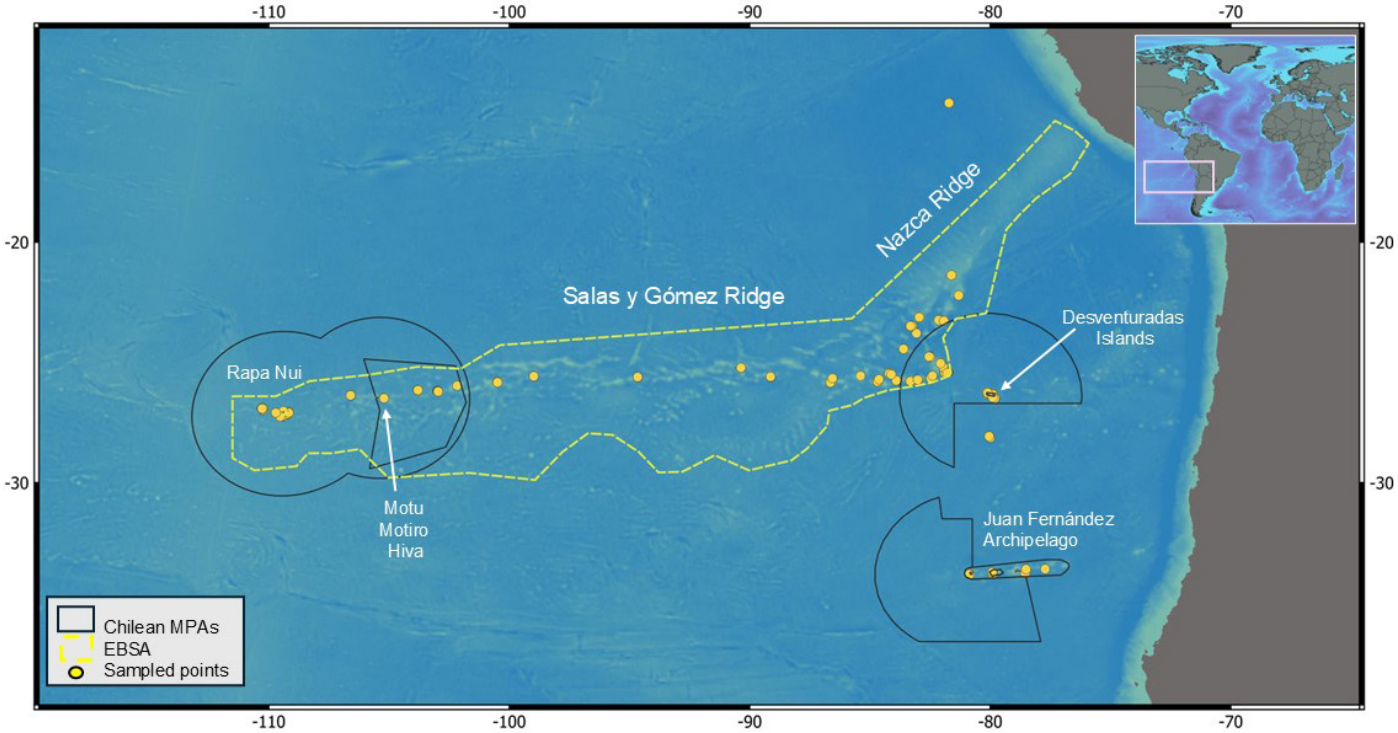
The 2024 Seamount Science Summit – Ecological Insights Workshop gathered 26 experts who provided key recommendations for managing seamounts as vulnerable marine ecosystems under General Assembly resolution 59/25. To date, only the Northwest Atlantic Fisheries Organization has fully implemented these recommendations, designating all seamounts within its regulatory area as vulnerable marine ecosystems and prohibiting bottom-contact fishing (NPFC, 2024).

South-East and West Pacific

Underexplored seamounts in the South-East Pacific basin (see figure VI) are concentrated along three major ridges: the Salas y Gómez, Nazca and Juan Fernández, hosting more than 144 seamounts, 51 of which lie within the EEZ of Chile, with summits ranging from 0 to 2000 m deep.

Recent expeditions by the Schmidt Ocean Institute (SOI, United States of America), the Japan Agency for Marine-Earth Science and Technology and the Center for Ecology and Sustainable Management of Oceanic Islands (ESMOI, Chile) surveyed 32 seamounts and discovered more than 34 uncharted ones. South-East Pacific seamounts are recognized as biodiversity hotspots, featuring 150 new species from the SOI 2024 cruises, including habitat-forming, endemic species and pristine ecosystems, earning recognition as ecologically or biologically significant marine areas. High ecological connectivity prevails in the region, supporting the resilience of marine populations across the Pacific.

Figure VI
South-East Pacific basin



Source: Ariadna Mecho.

Chile has established large-scale MPAs, covering the Rapa Nui and Desventuradas ecoregions. Peru has created a MPA located in the eastern Nazca Ridge. Over 73% of the ridges and associated seamounts still lie in areas beyond national jurisdictions, vulnerable to human activities (i.e. fishing, potential deep-sea mining, floating plastic debris and microplastics). International stakeholders are working to establish the first "blue corridor" to protect and ensure the long-term health of biodiversity (Wagner and others, 2021; Delgado and others, 2022; Boteler and others, 2022; Chavez-Molina and others, 2023; Gaymer and others, 2025).

In the South-West Pacific Ocean, recent research efforts shed light on benthic communities, megafauna and biophysical coupling on seamounts off New Caledonia (supplementary table 5). In New Zealand, an updated database now includes nearly 3,000 features.

Indian Ocean

The pelagic diversity, taxonomy, distribution, migration, ecotoxicology, trophic and biophysical interactions, connectivity and observations of physical phenomena along the South-West Indian Ridge, Sandes, La Pérouse, MAD-Ridge and Walters Shoal seamounts have been investigated since 2016 with French, German, British and Norwegian research efforts (see figures VII and VIII; Laptikhovsky and others, 2017; Letessier and others, 2017, 2019; Read and Pollard, 2017; Rogers, 2018; Annasawmy and others, 2019, 2020a, 2020b, 2024; Annasawmy, 2019; Hosegood and others, 2019; Cherel and others, 2020; Harris and others, 2020; Marsac and others, 2020; Noyon and others, 2020; Roberts and Ternon, 2020; Rocke and others, 2020; Yesson and others, 2021; Diaz and others, 2023; Diaz, 2023; Swanborn and others, 2023; Yutsis and others, 2023; Eager, 2024; O'Hara, 2024; Robinson and others, 2024) (supplementary table 6).

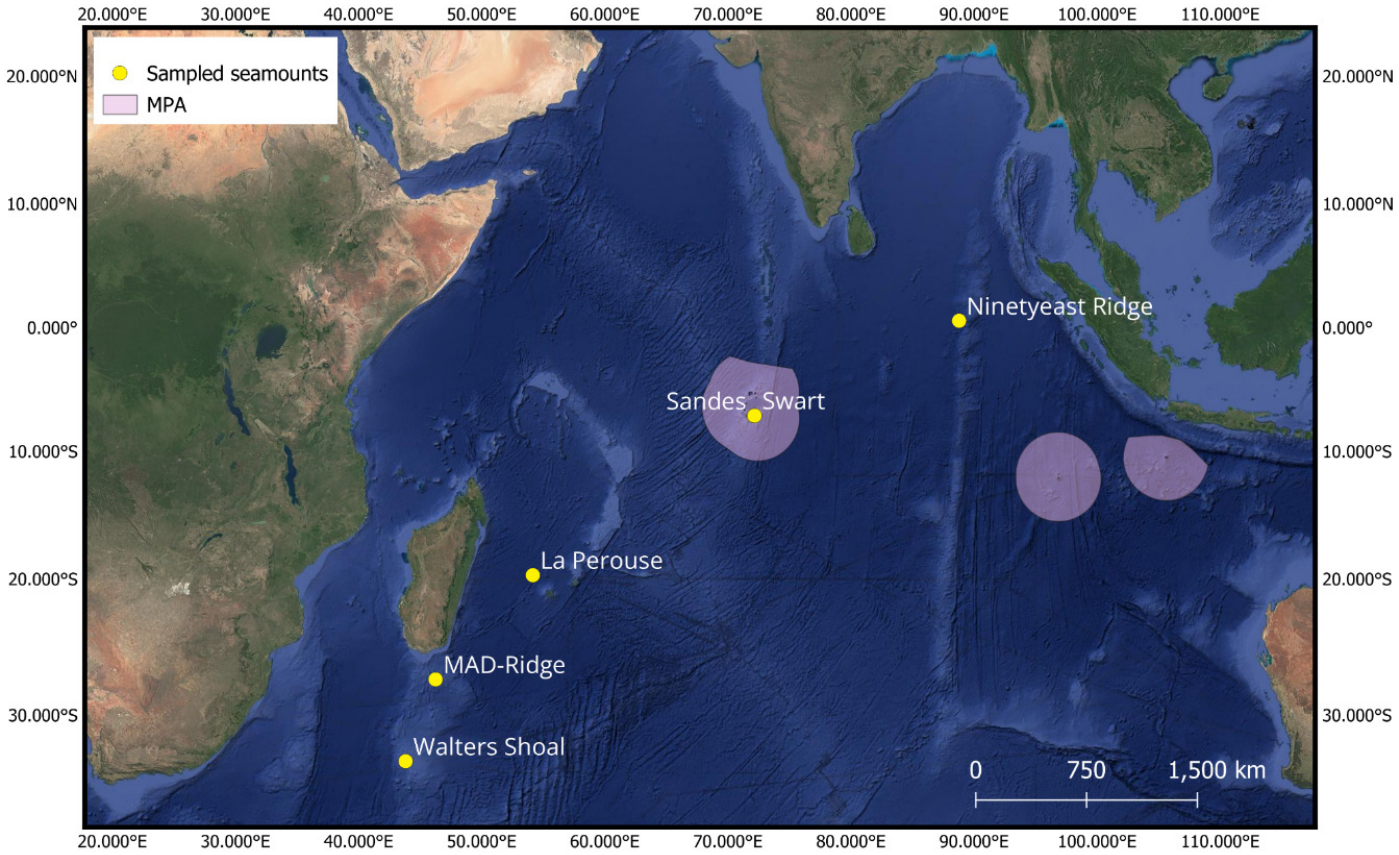
Several seamount paradigms were questioned:

(a) The seamount oasis effect was observed on some South-West Indian Ridge seamounts and for specific taxa but was not widespread across Indian Ocean seamounts.

(b) Lack of Taylor cap formation (trapped/enclosed circulations over seamount summits) under intense mesoscale eddies (rotating cyclonic or anticyclonic water masses) and over shallow seamounts.

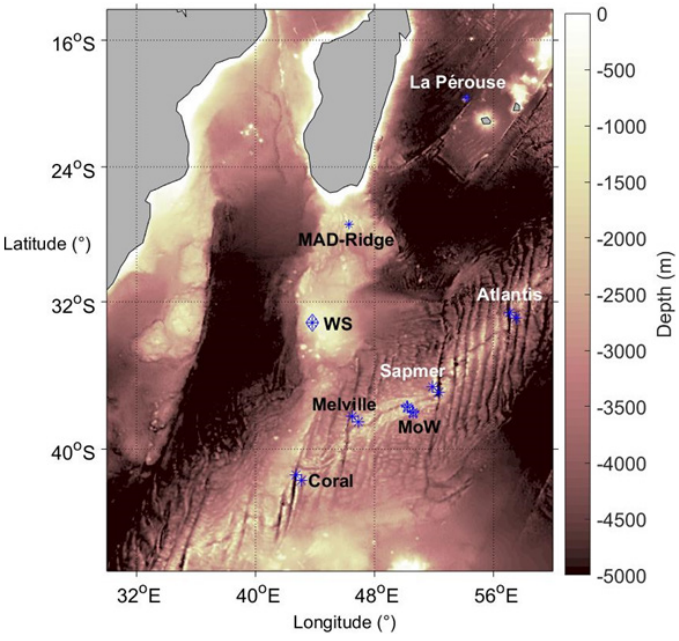
(c) Seamounts are not hotspots of micronekton diversity and densities (Annasawmy and others, 2019, 2020a; Marsac and others, 2020).

Figure VII
Indian Ocean seamounts and marine protected areas



Source: Dannielle Eager.

Figure VIII
South-West Indian Ocean seamounts



Source: Annasawmy, 2019.

The lanternfish *Diaphus suborbitalis*, which is a key trophic link between plankton and top predators and which contributes to the biological carbon pump by transporting carbon from the surface to deeper waters through diel vertical migration, has been observed exclusively at seamounts to date and not in open-ocean waters (Annasawmy and others, 2019, 2024, 2025; Cherel and others, 2020). Seamounts are distinct topographic barriers in the ocean, affecting the trophic connections between micronekton, which feed on zooplankton and which migrate from deeper waters to the top 200 m at night and those which do not migrate (Annasawmy and others, 2024).

The habitat preferences of key marine organisms at seamounts of the Indian Ocean are significant in the context of ecosystem health and potential conservation measures in the face of anthropogenic threats such as fishing and plastic pollution (Annasawmy, 2019). In 2022, the Western Indian Ocean National or International Seamounts, Banks and Submarine Structures Network (WIO NOISE) was launched, gathering regional researchers, students, policy makers and institutions interested in marine ecosystems' functioning, their exploitation,

conservation and governance associated with seamounts and shallow topographic structures in national waters, continental shelves, as well as in the high seas of the western Indian Ocean.

Southern Ocean

A number of seamounts and ridges of the Southern Ocean have been sampled in recent years (supplementary table 7). The interaction of the Antarctic Circumpolar Current (ocean current flowing from west to east around Antarctica) with seamounts generates upward movements, facilitating iron injection, hence fuelling productivity which attracts megafauna (Sergi and others, 2020). Significant research has been made on sedimentary cover at Jiawang seamount, contributing to understanding the formation process of seafloor deposits (Cui and others, 2023). The first observation of thermophilic and hyperthermophilic microorganisms, important for biogeochemical processes such as iron oxide deposition (Emerson and Moyer, 2002), were made at Orca seamount (Rodrigo and others, 2018). Seamounts and ridges of the Ross Sea have also been surveyed.

4. Pressures

Seamounts of the global ocean are under intensive fishing pressures (Baco and others, 2019, 2020, 2023a; Morgan and Baco, 2021), plastic contamination affecting marine life and ocean acidification (see supplementary table 8 for seamount locations). Mining exploration contracts are increasingly being issued in the global ocean which coincides with vulnerable marine ecosystems and conservation priority areas (Rogers, 2019).

Potential mining of cobalt-rich crusts represents an important pressure facing seamounts in the coming years. Habitat removal and sediment plume effects are the top risk sources likely to affect community structure, biodiversity, reproductive capacity, trophic ecology, behaviour and population connectivity of seamount benthic, benthopelagic and pelagic communities. Seamount communities are highly vulnerable with possible impacts across ecological scales, from species to the entire community. Recovery times are estimated to be over 100 years and the scale of impact is estimated between 1 km^2 and 10,000 km^2 (Washburn and others, 2019). The one existing study to date of impacts from a seamount mining test has found significant, sustained decreases in the density of mobile epifauna and highly mobile swimmers that persisted both one month and one year after the disturbance in addition to dead and damaged sessile benthic megafauna that were crushed or removed by the excavator (Washburn and others, 2023).

The first comprehensive study of Indian Ocean seamounts has demonstrated the effects of a warmer ocean causing lower productivity levels, lower trophic values of pelagic organisms and potential shifts in food web structure (Annasawmy and others, 2024). A decrease of 28% to 100% in suitable habitats, including seamounts, for cold-water coral species of the North Atlantic has been forecasted due to climate change (Morato and others, 2020).

Time series surveys off New Zealand and Tasmania highlighted the role of untrawled patches and unfished seamounts in post-fishing recruitment, with observations on Graveyard Knoll indicating the first signs of stony coral recovery 15 to 20 years after fishing ceased (Williams and others, 2020; Clark and others, 2021, 2022a). A 2022 survey by the National Institute of Water and Atmospheric Research following the Hunga Tonga-Hunga Ha'apai volcanic eruption in Tonga revealed benthic devastation from pyroclastic flows, except where the seamount features provided shelter for communities which were unaffected (Seabrook and others, 2023).

5. Key remaining knowledge and capacity gaps and new gaps

Despite significant progress, key knowledge and geographical gaps remain about seamount ecology, bathyal ecosystems, seamount functioning, recruitment and connectivity within and between seamount communities, anthropogenic pressures (linked to pollution, fishing, ocean warming, expansion of oxygen minimum zones) and management in areas beyond national jurisdiction and seamounts of the Arctic, Southern and Indian Oceans. Lack of global time series data introduces uncertainties in seamount observations, assumptions and conclusions. The knowledge gaps on seamount crusts are substantial and the lack of experimental data makes assessing the environmental risks of potential deep-sea mining of seamounts challenging.

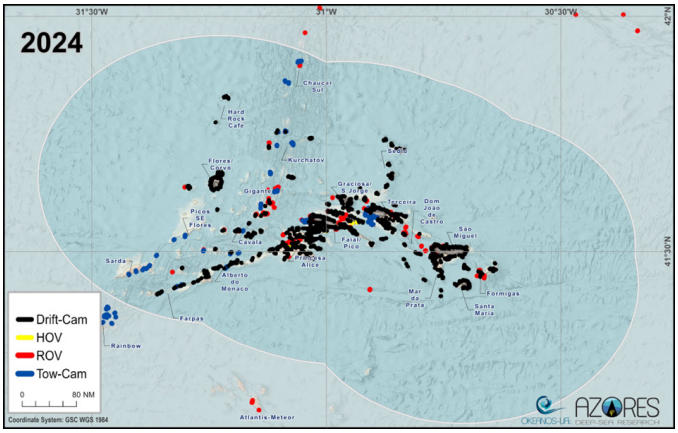
The effect of multiple stressors on seamount disturbance and effectiveness of management actions still remain to be assessed. Although data and observations are increasingly findable, accessible, interoperable and reusable, several years of embargo are generally placed on collected data, thereby reducing scientific progress and collaborations. Local, traditional and Indigenous knowledge is still not taken into account in seamount research from many regions of the world's ocean.

6. Outlook

Individual seamounts exhibit unique characteristics that influence biophysical processes and seamounts are interconnected to each other. Seamounts are facing significant and increasing anthropogenic pressures, making further study of these complex ecosystems a high priority. Integrating artificial intelligence into advanced technologies that monitor deep-sea seamount ecosystems on longer timescales is crucial, as limited research on seamount fauna hinders understanding of their biogeography. Further exploration and data collection are needed for seamount detection, assessment and protection. Initiatives such as the scientist ashore programme implemented during the 2024 NA161-169 expeditions of North Pacific seamounts by the National Oceanic and Atmospheric Administration ocean exploration via the Ocean Exploration Cooperative Institute with more than 800 ship-to-shore participants, over 55,000 live stream views, over 1 million social medial views, with full data access,[1] facilitate global collaboration and will significantly build scientific and management capacity. While it is premature to fully assess the impacts of such initiatives, they are expected to enhance seamount research by accelerating discoveries, refining habitat models, increasing public engagement and providing insights into seamount ecosystems that may inform future management strategies. Cost-effective deep-sea research enhances large spatial-scale biodiversity data observation at seamounts (see figure IX; Annasawmy and others, 2025). For a more holistic view of seamount ecosystems, local, traditional and Indigenous knowledge must be taken into account.

Figure IX

Seamount observations in the Azores (North Atlantic) using cost-effective technologies (drift-cameras and tow-cameras, human-operated vehicles, remotely operated vehicles)



Source: Telmo Morato.

[1] https://nautiluslive.org/expeditions/2024.

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Subchapter 5M Abyssal plains

Key points

- Despite improvements in understanding abyssal biodiversity, knowledge gaps in abyssal evolution and biogeography, connectivity and biotic responses to natural temporal and anthropogenic change remain. The incomplete knowledge of abyssal systems reflects major challenges in sampling this vast and remote area.
- Abyssal environments support processes underlying deep-sea and global ecosystem functioning and link closely to surface production and pelagic processes.
- Marine carbon dioxide (CO_2) removal and ocean-based carbon interventions may affect abyssal systems directly if deployed on the seafloor or affect pelagic processes that could indirectly result in changes in abyssal ecosystem function.
- Despite knowledge improvements on abyssal biodiversity linked to deep-sea mineral exploration, full assessment of impacts of exploitation on abyssal ecosystems requires further scientific research.

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1. Introduction

Abyssal plains refer to the deep-ocean floor between 3,000 and 6,000 m. Potentially lower alpha biodiversity characterizes abyssal plains relative to bathyal depths (Rex and Etter, 2010). Yet, given their vastness, abyssal plains likely host similar or more species globally compared to other deep seafloor habitats. Because most abyssal plains occur beyond national jurisdiction, the diversity and genetic resources they contain fall under the recently adopted Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction,[1] which aims at ensuring the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. In addition, mineral resource presence and the abyss's potential to help mitigate climate change increase interest in abyssal habitats.

While abyssal environments were briefly described in the first *World Ocean Assessment*, a detailed account of abyssal biodiversity was offered in the second *World Ocean Assessment*. Building on these efforts, the present review examines current regional abyssal biodiversity knowledge and how abyssal biodiversity may respond to future changes.

2. Environmental change since the second *World Ocean Assessment*

Changes in the overall status

Ongoing climate change and ocean surface warming will likely carry through to the water column and abyssal depths (Levin and Le Bris, 2015). Models suggest that many abyssal ocean regions will exceed their historic range of variability over the next decade (Levin and others, 2020). Sutton and others (2024) documented warming at full ocean depth east of New Zealand, driven by ocean heat gradient changes between mid and high latitudes that reduce local flows of deeper and colder sub-Antarctic water masses. These patterns continue at the global level (Johnson and Purkey, 2024). In addition, there is growing recognition that shifting — and often declining — ocean productivity (Bryndum-Buchholz and others, 2019) may be linked to abyssal ecosystems that depend on surface production; these changes, combined with rising temperatures, could affect abyssal biodiversity and ecosystem function (McClain and others, 2012; Smith and others, 2018).

Documenting long-term changes in abyssal communities remains challenging, but some long-term abyssal observations show that climate cycles likely alter communities. At the Porcupine Abyssal Plain (48°50'N 16°30'W, 4850 m depth), scavenging amphipod species composition varies with the Atlantic Multi-decadal Oscillation index (Horton and others, 2020), and at Station M (34°50'N, 123°00'W, 4100 m depth) off the California coast, megafaunal variation may link to heat anomalies (Kuhnz and others, 2020). Climate-driven changes in organic matter supply explain some changes in seafloor oxygen consumption (Smith and others, 2018), feeding activity (Durden and others, 2020) and benthic community structure and standing stocks (Horton and others, 2020; Kuhnz and others, 2020). Increased data resolution shows episodic carbon fluxes vary more temporally than thought (Huffard and others, 2020), while deep-sea fossil records over longer timescales indicate reorganization of deep-sea benthic communities with climatic changes, such as reduced deepwater formation and changes in temperature and particulate organic carbon flux (e.g. Cronin and others, 1996; Yasuhara and others, 2014; Yasuhara and others, 2025).

Historically, most direct human-induced pressures (e.g. trawling, hydrocarbon drilling) have been focused on shelf and bathyal depths (Glover and Smith, 2003), but anthropogenic alterations are deepening (Ramirez-Llodra and others, 2011). Recent studies document organic pollution and microplastics at abyssal depths and deeper (Jamieson and others, 2017; Abel and others, 2021; Nakajima and others, 2021). Some argue that the greening of global society will require advancing blue economy initiatives, such as exploitation of abyssal mineral resources and marine CO_2 removal and ocean-based carbon interventions (see below).

[1] www.un.org/bbnjagreement/en.

Understanding potential impacts from deep-sea mineral exploitation activities on abyssal habitats and their biodiversity has improved following extensive baseline surveys and experimental studies in the abyssal Clarion-Clipperton Zone in the Pacific Ocean (Muñoz-Royo and others, 2021; Muñoz-Royo and others, 2022; Jones and others, 2025). Trials of polymetallic nodule collectors in the Clarion-Clipperton Zone spurred scientific monitoring (e.g. Gazis and others, 2025) that identified limited impacts on densities and diversity inside test tracks against a background of substantial spatial and potential temporal variation (Lefaible and others, 2024). Gravity flow may dominate benthic sediment plumes, limiting their extent compared with previous predictions (Muñoz-Royo and others, 2022). Despite limited information on the ecological and biological effects of suspended sediment concentrations in abyssal environments (Hauton and others, 2017), multiple stress responses may occur (Stenvers and others, 2023). Effects on community structure (Simon-Lledó and others, 2019a), functioning (de Jonge and others, 2020; Vonnahme and others, 2020) and ecosystem services (Orcutt and others, 2020) may persist for decades (Jones and others, 2025). The timescales of recovery and species-specific responses remain an important knowledge gap and require realistic mining tests and comprehensive monitoring (e.g. Lefaible and others, 2024). Anticipated impacts of chemical toxicity, noise and light related to deep-sea mineral exploitation are equally poorly documented (Williams and others, 2022). Developing restoration capacity in deep-sea and abyssal ecosystems, an area of active research (Danovaro and others, 2021), will draw on proposed novel technologies (Aguzzi and others, 2024).

Effects of change and interaction with other components of the abyssal marine system

Marine CO_2 removal and ocean-based carbon interventions incorporate diverse potential approaches, including artificial iron fertilization, which will likely change the quantity and quality of carbon flux to the abyss (Keller and others, 2018). A fossil study shows that not only warming but also changes in dust flux and resulting iron fertilization alter deep-sea ecosystems (Yasuhara and others, 2025). Some deep-ocean carbon technologies may directly alter abyssal communities, indicated in small-scale experiments (Barry and others, 2013) and natural analogue studies of organic falls (Amon and others, 2017; Harbour and others, 2021). Precautionary management of marine CO_2 removal and ocean-based carbon interventions should also consider potential second-order effects on abyssal seafloor systems and often-overlooked interactions and feedback between carbon reservoirs (Keller and others, 2018). Importantly, even if these climate mitigations stabilize global temperatures, climate trends and changes in global ocean circulation and shallow-water and deep-sea marine systems may continue (e.g. Sigmond and others, 2020).

3. Region-specific changes in benthic biodiversity knowledge

Arctic Ocean

A recent synthesis revealed high diversity of deep Arctic geomorphological features and a paucity of biodiversity data in deep basins (Ramirez-Llodra and others, 2024). Abyssal Arctic fauna is highly sensitive to sea-ice melt and the resulting enhanced algal bloom and flux (Boetius and others, 2013). Ongoing projects are investigating the Arctic seafloor response to changing ice conditions[2] to identify changes at species and community levels, but also in functional characteristics across the abyssal Arctic Ocean. Biogeographic distribution information over large spatial scales merits further investigation.

Baltic Sea, North-East Atlantic Ocean and Mediterranean Sea

The Baltic Sea does not reach abyssal depths and the Mediterranean Sea's abyss (Calypso Deep, Ionian Sea) remains poorly investigated. Hence, the focus is on comparatively well-described and studied North-East Atlantic Ocean abyssal systems, including newly discovered rocky habitats and biodiversity (Riehl and others, 2020). Integrated taxonomic study demonstrates the importance of knowledge on habitat heterogeneity for inferring large-scale biodiversity patterns (e.g. Schmidt and others, 2024). Understanding of deepwater mass properties and how they influence biodiversity and biogeography of North-East Atlantic abyssal ecosystems has improved, including the role climatic changes play in these processes

[2] See www.arctic.ac.uk.

(Puerta and others, 2020). Improved understanding of deep-sea change critically requires abyssal temporal observations. Despite the fact that there are only a few deep-sea long-term monitoring stations, those that exist have provided crucial information. These stations include the Porcupine Abyssal Plain in the North-East Atlantic, operational since the mid-1980s (Horton and others, 2020). Recent insights from the Porcupine Abyssal Plain highlight regional oxygen differences over decadal timescales (Ruhl and others, 2025). Although funding cuts threaten these time series, assessing long-term abyssal ecosystem changes requires extended temporal observations. Paleoecological data from deep-sea sediment cores such as the International Ocean Discovery Programme provide historical biodiversity time series spanning much longer durations (e.g. tens of thousands to millions of years (Yasuhara and others, 2008; Thomas and Gooday, 1996)) and causally link deep-sea diversity to deep-sea temperature (Doi and others, 2021) as an important driver of abyssal biodiversity. A better understanding of abyssal biodiversity dynamics and its drivers will require more scientific effort.

South Atlantic Ocean and wider Caribbean

Bridges and others (2023) recently emphasized the paucity of recent abyssal biodiversity studies in the Central and South Atlantic region. Shallow coastal studies dominate Caribbean Sea biodiversity research. The scarce available information shows some regional megafauna variation in the Caribbean abyss (Briggs and others, 1996) and reduced biodiversity in the continental rise-abyssal zone relative to slope depths (Hernández-Ávila and others, 2018).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf, Strait of Malacca and South China Sea

Noting that the Gulf of Aden, the Persian Gulf and the Strait of Malacca do not reach abyssal depths and the limited Red Sea abyssal areas, these seas are omitted here and the focus is on the Indian Ocean (including the Bay of Bengal) and the South China Sea.

Despite some abyssal Indian Ocean biodiversity records in the Ocean Biodiversity Information System (Thomas and others, 2024) data remain very limited (Saraswat and others, 2022). The presence of deep-sea minerals motivated Indian-led abyssal research since the 1980s, but efforts have slowed, reinforcing a need for wider Indian Ocean biodiversity research.

In the deep South China Sea, biodiverse communities on large plastic debris dumps demonstrate plastics as habitats for deep-sea epibenthos (Song and others, 2021). South China Sea biodiversity knowledge generally remains limited for abyssal depths (Ng and Tan, 2000; Liu, 2013). Deep-sea biological investigations in the South China Sea in the last decade have emphasized bathyal cold seep habitats (e.g. Wang and others, 2022).

North Pacific Ocean

Since the publication of the second *World Ocean Assessment*, considerable new abyssal knowledge has accrued for the North Pacific Ocean, in particular the Clarion-Clipperton Zone with its abyssal polymetallic nodule fields. Higher species richness may characterize some Clarion-Clipperton Zone fauna compared to other abyssal habitats (Stewart and others, 2023). Regional Clarion-Clipperton Zone animal species richness is estimated at 6,000 to over 8,000, 88% to 92% of which are undescribed (Rabone and others, 2023). Although experts describe new abyssal species each year (Rabone and others, 2023) and target new geographic locations (Bribiesca-Contreras and others, 2022), limited taxonomic expertise constrains descriptions of new species. Regional-scale syntheses have enabled better understanding of biodiversity and identified knowledge gaps and standardization issues (e.g. Wear and others, 2021; Hauquier and others, 2019; Smith and others, 2021; Stewart and others, 2023; Simon-Lledó and others, 2023a). Findings include linking basin-scale productivity gradients and a major biogeographic discontinuity related to the carbonate compensation depth (Simon-Lledó and others, 2023a). High environmental heterogeneity characterizes abyssal environments (Washburn and others, 2021), noting the role of topography (Simon-Lledó and others, 2019a), substratum (Francesca and others, 2021; Simon-Lledó and others, 2019b), episodic food supply (Simon-Lledó and others, 2023b) and ecosystem engineers (Danovaro and others, 2024; Quintanilla and others, 2022).

Despite increasing studies of abyssal connectivity, understanding remains limited and inconsistent among faunal groups (Taylor and Roterman, 2017), an important gap in the context of potential deep-sea mineral exploitation. Most abyssal studies note the high proportion of rarely sampled species (McClain, 2021), but population genetic studies at multiple locations suggest well-connected populations over broad regions (Stewart and others, 2023; Taboada and others, 2018). At the global scale,

biogeophysical environments broadly define deep-sea biogeographic provinces (Watling and others, 2013; Maureaud and others, 2023), although Watling and Lapointe (2022) found weaker support using lower bathyal data for anthozoans. Brandt and others (2019) noted that the hadal Kuril Kamchatka trench potentially limited connectivity and created faunal discontinuities in some abyssal faunal groups in the North-West Pacific Ocean.

South Pacific Ocean

Outside areas of mineral resource interest, few studies have addressed South Pacific abyssal environments. However, in 2024, the Ocean Census Programme sampled the Bounty Trough east of New Zealand to 5000 m depth, focusing on biodiversity discovery (Mills and others, 2024) and documented numerous new species and extended many distributional records.

The Hunga Tonga-Hunga Ha'apai eruption off Tonga in 2022, among the largest in recent history (Proud and others, 2022; Seabrook and others, 2023), catalysed several scientific voyages to map changes in topography and faunal communities. Few epifauna and macro-infauna survived the ash that blanketed hydrothermal vent fields more than 80 km from the volcano (Beinart and others, 2024) and adjacent abyssal plains, except where topographic highs such as knolls and hills provided shelter from direct sediment flows (Mackay and others, 2022; Seabrook and others, 2023). Surveys from 2024 and 2025 are investigating the recovery of benthic communities from this eruption. In addition, efforts to map and prioritize hydrothermal vent ecosystem protection at a global scale continue (Menini and others, 2023).

Southern Ocean

Noting limited advances in knowledge regarding biodiversity and biogeography on Southern Ocean abyssal plains, researchers nonetheless report new species and habitats. Sampling of a Ross Sea seamount at 3,380 m depth revealed seven new species (Lörz and others, 2023). Numerous hydrothermal vents reported from the South Sandwich Arc in the Southern Ocean (Linse and others, 2022) lack characteristic vent or seep megafauna, although taxa in the vicinity varied greatly.

4. Implications for achieving the targets of the 2030 Agenda for Sustainable Development and its Sustainable Development Goals

Society must determine the appropriate balance between economic and socioclimatic gains and the environmental consequences of human activities, including deep-sea mineral exploitation and marine CO_2 removal.

Long-term research of abyssal ecosystems demonstrates community responses to temporal changes in organic carbon flux, underscoring their critical role in global ocean processes. The increase in environmental baseline studies — particularly in the context of mineral exploration in the Clarion-Clipperton Zone, the Central Indian Basin and the North-West Pacific Ocean — has accelerated abyssal taxonomic and ecological research, as reflected in a stocktaking report on the contribution of the International Seabed Authority (ISA) to the scientific objectives of the United Nations Decade of Ocean Science for Sustainable Development. However, the need for biological research, environmental monitoring and evidence-based decision-making to guide sustainable management and conservation of these ecosystems remains, reflecting requirements described under the United Nations Convention on the Law of the Sea and the regulatory mandate of ISA.

5. Key remaining knowledge and capacity gaps and new gaps

Despite increased biological sampling in areas of interest for mineral resources, considerable knowledge gaps remain (Amon and others, 2022). These gaps include understanding of trophic relationships, life histories, population and ecosystem connectivity and natural temporal variability of communities. Roest and others (2024) prioritized ecosystem-level functioning as a key management focus, recognizing the impracticality of obtaining detailed species-level data. Key knowledge gaps include:

- A global paucity of abyssal biodiversity knowledge, particularly for hard-bottom habitats;
- Knowledge of species geographic ranges, connectivity patterns and resilience of assemblages to climate stressors and human activities in the abyss;

- Emerging geoengineering technologies may present new opportunities to combat global change, yet may also pose risks of impact to abyssal ecosystems. Sustained monitoring, fundamental ecological research and evidence-based governance are needed.

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Subchapter 5N
Pelagic domain

Key points

The pelagic domain encompasses the entire water column and is the largest oceanic region. Due to its vastness and limited accessibility, it remains less studied and understood than its benthic and intertidal counterparts. The existing knowledge underscores its biological richness and essential contribution to ecosystem functions. It also offers significant potential for humans, providing valuable ecosystem services such as living resources, energy and climate regulation.

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1. Introduction

Key components and structure

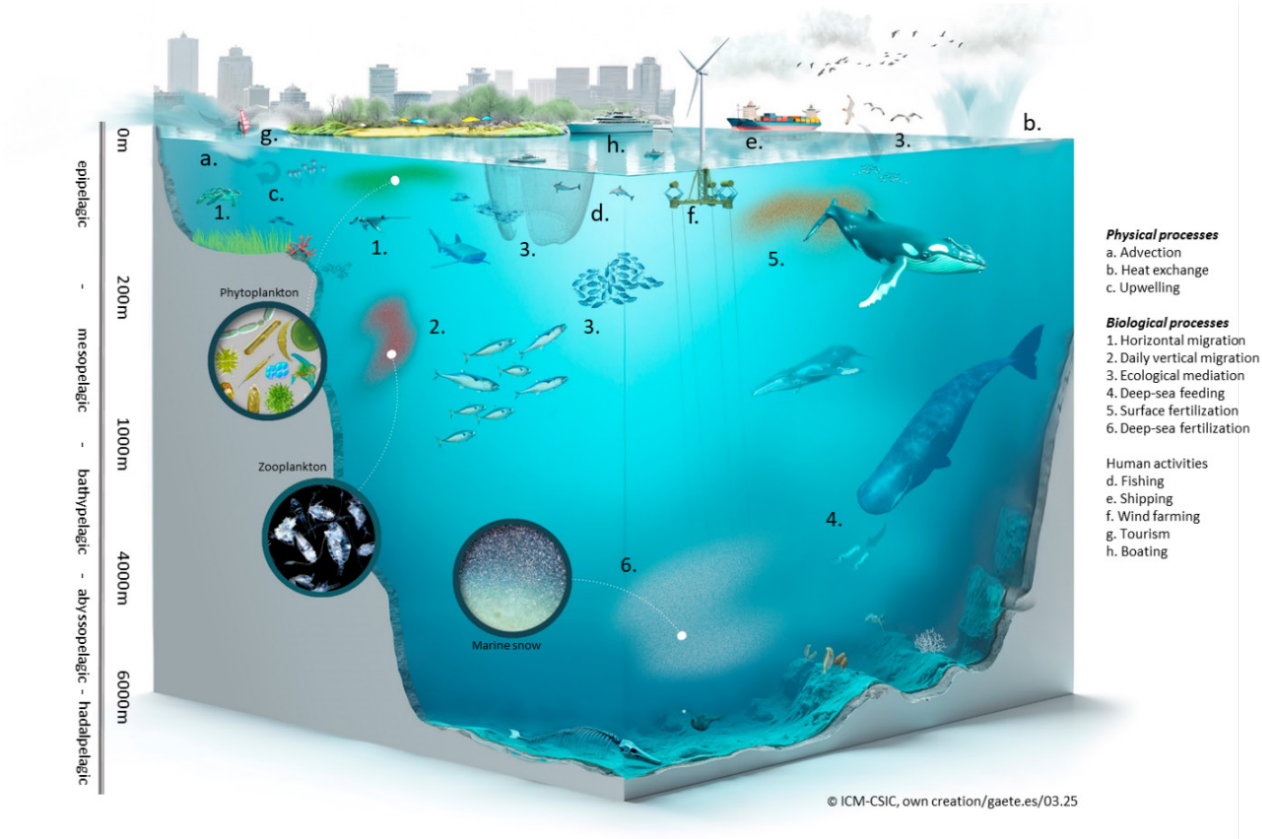
From the Latin *pelagus*, the pelagic domain refers to the open-ocean environment, consisting of all the organisms that live within the water column, rather than on the ocean floor or near the coast. A key characteristic is the high mobility and dynamism of its organisms, which are not anchored to substrate and move through the water column. Their movements link habitats and drive processes like benthopelagic coupling (see figure I). An exception to that mobility is some mesopelagic species that are non-migratory, particularly the *Cyclothone* genus that is largely responsible for what are known as the deep scattering layers, ubiquitous features of the mesopelagic (Sarmiento-Lezcano and others, 2023) and bathypelagic depths (Peña and others, 2021).

The pelagic domain is influenced by physical and biogeochemical factors that create distinct and dynamic habitats for marine life at different depths (see figure I). It is subdivided into zones based on light penetration: epipelagic (0–200 m), mesopelagic (200–1,000 m), bathypelagic (1,000–4,000 m), abyssopelagic (4,000–6,000 m) and hadalpelagic (more than 6,000 m) zones. This classification aids its description, although oversimplification may misrepresent ecosystem processes (Eduardo and others, 2024).

Past drivers and pressures

Since the 1800s, the key factors controlling the pelagic domain underwent significant shifts, driven by human-induced climate change. These changes are altering species distributions and productivity, biodiversity and the overall health of the oceans (Williamson and Guinder, 2021), with significant socioecological and economic consequences. Human activities like intense fishing, energy production and global trade are also increasingly affecting the pelagic zone (see figure I), with rising impacts now reaching even remote and once-pristine areas (Paolo and others, 2024).

Figure I
Schematic representation of the pelagic domain



Source: Image: ICM-CSIC, own creation/gaete.es/03.25.

Note: Main regions and species type are represented, along with some key ecological processes and human activities that accumulate in the pelagic domain.

2. Scientific advances since the first and second *World Ocean Assessment*

New discoveries and technological advances

Advancements in observational technologies have enhanced the ability to monitor Earth and wildlife, utilizing high-resolution data from sensors in various environments (Joo and others, 2022; McCauley and others, 2024). Research vessels now serve as motherships for robots, enabling extensive data collection and multidisciplinary studies (Miller and Virmani, 2023). The Biogeochemical Argo programme has expanded global insights into ocean productivity and dissolved oxygen (Izett and others, 2024; Jemai and others, 2021; Stoer and others, 2023).

Environmental DNA techniques have enhanced biodiversity understanding across ecosystems (Deeg and others, 2023; Zhang and others, 2020). They provide new insights into the diets of pelagic species, particularly informing the contribution of gelatinous zooplankton (Dischereit and others, 2024). On the other hand, advancements in the study of trophic ecology and ecosystem functioning include compound-specific stable isotope analyses (Gimenez and others, 2023; Stahl and others, 2023).

New assessments and modelling efforts

The latest Earth system models from the Coupled Model Intercomparison Project have projected greater warming, acidification, deoxygenation and nitrate reductions in the ocean, with smaller declines in primary production compared with the previous model (Kwiatkowski and others, 2020). The latest models also better capture extreme events like marine heatwaves (Qiu and others, 2021). Species distribution models and marine ecosystem models now integrate complex data sets and environmental dynamics, simulating marine biomass on a global scale (Lotze and others, 2019; Tittensor and others, 2018). These models have revealed uncertainties and help project ecosystem responses to climate changes (Blanchard and Novaglio, 2024; Heneghan and others, 2021; Tittensor and others, 2021). Recent advancements in functional trait standardization have aided environmental DNA and their applications in ecosystem modelling, connecting ecosystem components based on functional roles and properties (Green and others, 2022; Heneghan and others, 2020; Pata and Hunt, 2023).

Emergent drivers and effects

Recent analyses have shown how changes in energy transfer efficiency due to ocean warming may lead to reduced biomass of fish and marine mammals, a phenomenon known as trophic amplification (Atkinson and others, 2024; Lotze and others, 2019).

Extreme ocean events have received increased attention due to their abrupt nature and severe impacts. Studies show spatial overlap and temporal synchronicity of compound extreme events, which exacerbate their effects (Amaya and others, 2023; Li and others, 2024). Recent advancements in ocean reanalysis models enable the analysis of vertical structures of these events (Wong and others, 2024; Zhang and others, 2023).

Emergent pollutants, transported through oceanic and atmospheric means, also pose an increasing risk to pelagic systems. Global levels may be exceeding planetary boundaries (Richardson and others, 2023).

3. Description of the current state and recent trends

Changes in physical and chemical states

Global ocean temperatures are rising, especially at high latitudes (figure II) (Garcia-Soto and others, 2021; Storto and Yang, 2024) (sect. 4, chap. 3). In addition, natural variability, such as the Pacific Decadal Oscillation and El Niño Southern Oscillation, affects regional trends (Johnson and Lyman, 2020). The 2023 El Niño led to record sea-surface temperatures, with the global average 0.23°C higher than in 2022, while Antarctic sea-ice extent reached unprecedented lows (Copernicus, 2023).[1]

Warming trends also increase the frequency and intensity of marine heatwaves (Collins and others, 2022; Oliver and others, 2021) (see figure III). Marine heatwaves affect marine ecosystems by altering species distributions and food web efficiency (Smith and others, 2023). They can trigger low-oxygen events, worsening

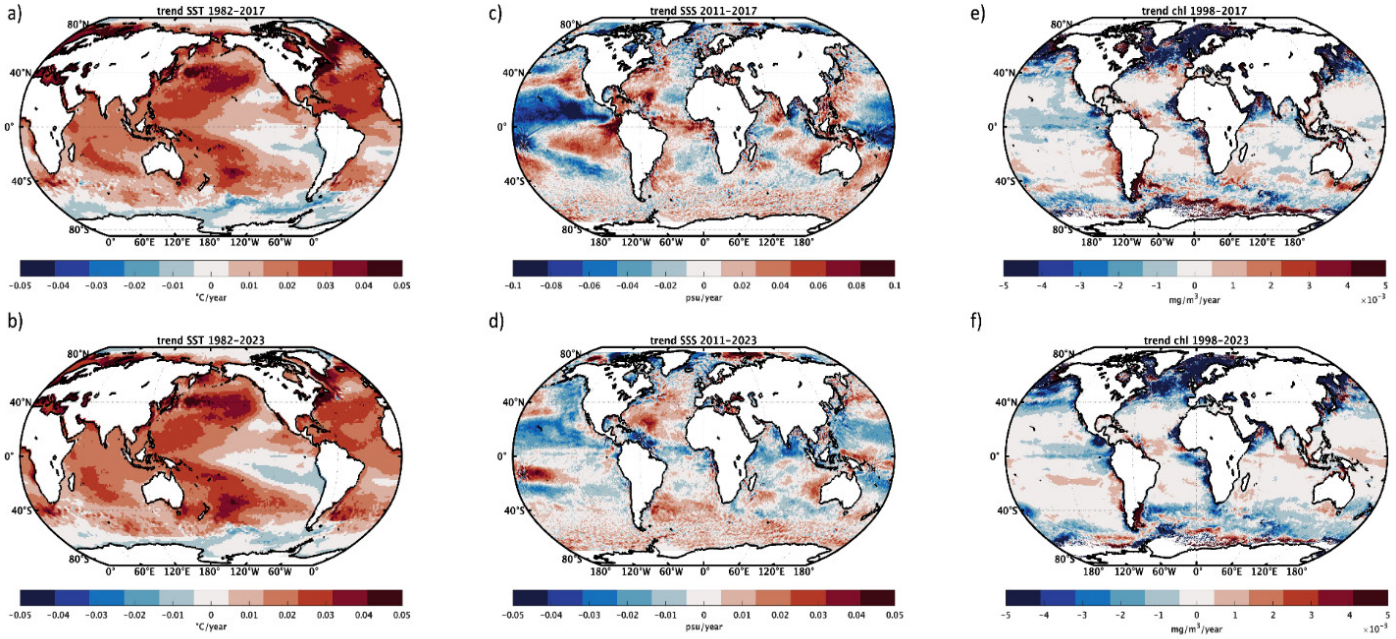
[1] See: https://marine.copernicus.eu/news/2023-northern-hemisphere-summer-record-breaking-oceanic-events.

ocean deoxygenation (Li and others, 2024) and leading to habitat compression (Jorda and others, 2020).

The ocean absorbs anthropogenic CO_2, leading to increased acidity (decreased pH) and decreased aragonite saturation state (Bednaršek and others, 2023; Garcia-Soto and others, 2021; Ma and others, 2023) (see sect. 4, chap. 3). Ocean salinity and circulation are also changing (see sect. 4, chap. 3) impacting the pelagic domain (see figure II) (Bograd and others, 2023; Ditlevsen and Ditlevsen, 2023; Douville and Cheng, 2024; Fox and others, 2023; Gutierrez-Guerra and others, 2024; Rahmstorf, 2024).

Figure II

Temperature trend for the period (a) 1982–2017 and (b) 1982–2023; salinity trend for the period (c) 2011–2017 and (d) 2011–2023; chlorophyll-*a* trend for the period (e) 1998–2017 and (f) 1998–2023



Sources: Salinity data from Kolodziejczyk and others, 2021; chlorophyll-*a* data downloaded from the Copernicus marine service website (see https://data.marine.copernicus.eu/products); and temperature data from NOAA OISSTv2.176 product, obtained from NOAA/OAR/PSL (see https://psl.noaa.gov/).

Changes in marine productivity and chlorophyll-*a* concentration

Marine productivity has declined across ocean basins, primarily due to ocean warming, increased stratification and reduced oxygen and nutrient fluxes (Boyce and others, 2010) (see sect. 4, chap. 3). Recent satellite data indicate ongoing declines in chlorophyll-*a* concentrations, affecting the reproductive performance of marine predators, in particular in the northern hemisphere (Sydeman and others, 2021). While strong natural variability masks climate-change effects on phytoplankton, trends in ocean colour reflectance are more detectable, revealing that low-latitude oceans have become greener (Cael and others, 2023). Negative extreme events decrease at high latitudes, while positive extremes intensify, especially along the circumpolar current (see figure IV).

Human activities

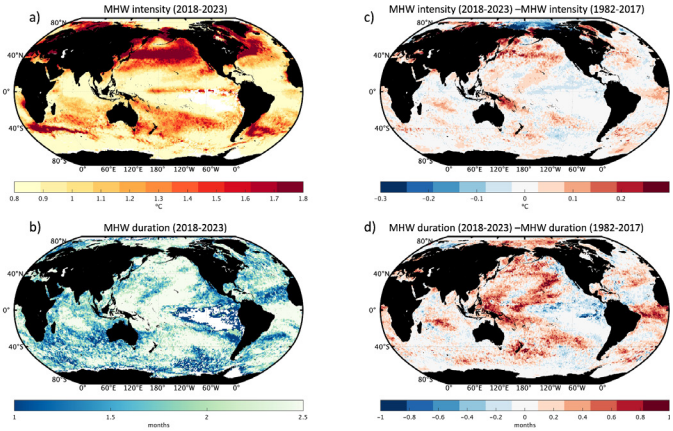
Plastic debris is increasingly found in marine organisms (Liu and others, 2023; Marmara and others, 2023; Wieczorek and others, 2018). Plastics affect marine ecosystems by influencing carbon sinking rates and oxygen levels (Kvale and others, 2023). Humans are exposed to plastics through contaminated seafood (Akhbarizadeh and others, 2020; Leslie and others, 2022; Marmara and others, 2023).

While small-scale trials for mesopelagic fish exist, they are not a significant target for commercial fishing, with total reported catches at 2.7 million tons since the 1950s (Pauly and others, 2021). Economic viability is limited by distance to fishing areas, high fuel costs, rapid fish deterioration and low fish density (Kourantidou and Jin, 2022; Paoletti and others, 2021; Vastenhoud and others,

2023). Rising demand for fishmeal and improved storage methods may make mesopelagic fisheries profitable in the future (Paoletti and others, 2021).

Figure III

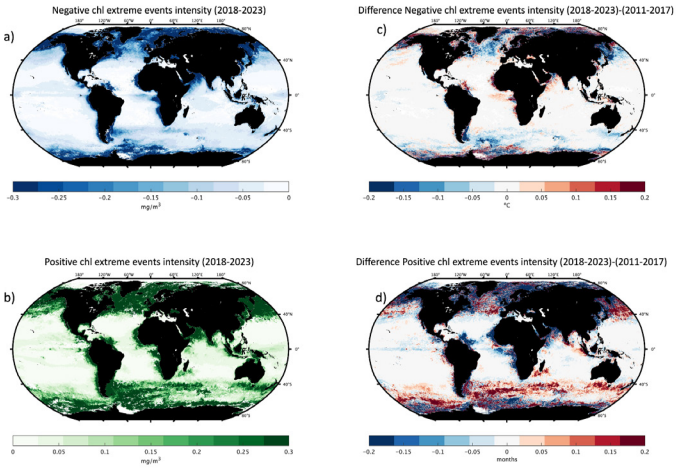
(a) Mean marine heatwave intensity for the period 2018–2023; (b) same, but for marine heatwave duration; (c) difference between mean marine heatwave intensity computed over the period 2018–2023 and mean marine heatwave intensity computed over the period 1982–2017; (d) same, but for marine heatwave duration



Source: Temperature data from NOAA OISSTv2.176 product, obtained from NOAA/OAR/PSL (https://psl.noaa.gov/).

Figure IV

(a) Negative and (b) positive extreme events of Chlorophyll-*a* intensity for the period 2018–2023; (c) differences between negative extreme events of chlorophyll computed over 2018–2023 and 2011–2017 (blue colours indicate that negative extreme events were more intense during 2011–2017); (d) same, but for positive extreme events of chlorophyll.



Source: Chlorophyll-*a* data from https://doi.org/10.48670/moi-00281 downloaded from the Copernicus marine service website: https://data.marine.copernicus.eu/products.

Key zones

The mesopelagic zone (200–1,000 m) covers 60% of the surface of the Earth and accounts for 20% of the ocean's volume. This community is vital to the biological carbon pump and the global carbon cycle, transporting carbon to depth through diel vertical migration (Anderson and others, 2019; Kiko and others, 2020) and mediating the flux of sinking carbon-containing particles (Baumas and others, 2021) (subsect. 5B, chap. 1). Mesopelagic fish and zooplankton contribute 16% each to the global biological carbon pump, corresponding to the sinking particulate organic carbon (POC) flux from surface waters (Archibald and others, 2019; Saba and others, 2021). Climate-driven changes are altering mesopelagic communities, impacting the biological carbon pump (Kiko and others, 2020).

Primary production in eastern boundary upwelling systems is disrupted by climate change, as sea-surface temperatures rise and upwelling winds intensify. Shifts in pelagic species are observed in upwelling systems, such as the California Current and Southern Benguela (Blamey and others, 2015; Fiechter and others, 2021).

The Arctic and Antarctic regions are highly vulnerable to climate change, in particular in their oceans and cryosphere. Changes in sea-ice conditions are leading to profound shifts in the magnitude and phenology of pelagic marine productivity pulses, typical of highly seasonal polar systems, with far-reaching implications for polar ecosystems and their roles in global biogeochemical cycles (see sect. 4, chap. 3 and subchap. 5K) (Willis and others, 2023).

Key species groups

Climate-driven declines in phytoplankton size and biomass have led to greater losses in higher trophic organisms like fish and marine mammals across the open ocean (Henson and others, 2022; Lotze and others, 2019). Ocean warming has also shifted zooplankton distribution, favoured smaller species and altered seasonal patterns of productivity (Benedetti and others, 2021; Ratnarajah and others, 2023). These shifts have large impacts on fish recruitment (Beaugrand and others, 2003; Jaspers and others, 2023; Johnston and others, 2022; Pinchuk and others, 2021; Steinberg and Landry, 2017) (see sect. 4, subchap. 4A).

Small pelagic fish contribute over 15% of energy flowing to top predators, supporting 22% of seabirds and 15% of marine mammals in assessed ecosystems (Ruzicka and

others, 2024). Small pelagic fish represent 43% of total fish production and 18% of global catches, (Ruzicka and others, 2024). Their worldwide status is complex and regionally variable (FAO, 2024). Historically, fluctuations in small pelagic fish populations have been linked to environmental variability, while high fishing pressure and competition among pelagic organisms play crucial roles (Alheit and Peck, 2019; Coll and others, 2024; Hilborn and others, 2022). These fluctuations significantly affect fisheries and predatory species of conservation concern. In 2023, El Niño conditions reduced the habitats of cold-water species like Peruvian anchoveta (*Engraulis ringens*), the world's largest monospecific fishery, leading to a 50% reduction in industrial landings compared with 2022. Such losses impacted local economies and global aquaculture due to the fishery's role in producing fishmeal and fish oil (see sect. 4, chap. 4).

Deep-pelagic fish are crucial for oceanic carbon sequestration (Eduardo and others, 2024; Klevjer and others, 2016; Saba and others, 2021) but they face threats from pollutants (Ferreira and others, 2023; Justino and others, 2022), potential exploitation from fisheries (Hidalgo and Browman, 2019; Pauly and others, 2021), the offshore oil and gas industry (Hawkins and others, 2023) and the emerging practice of deep-sea mining (Kung and others, 2021).

The open-ocean catch was estimated at 11 million tons per year in 2022, primarily consisting of species with open-ocean distributions (FAO, 2024). Global tuna catches reached 8.3 million tons in 2022, with 87% of world tuna stocks considered sustainably fished (FAO, 2024). Skipjack tuna (*Katsuwonus pelamis*) is the third-largest catch among harvested species, while some previously overfished stocks, like bluefin tuna (*Thunnus thynnus*), have recovered, demonstrating the benefits of effective management (Juan-Jordá and others, 2022). Not all species and stocks are assessed, however, in particular small tunas (Lucena-Frédou and others, 2021).

Chondrichthyans are highly vulnerable to overfishing and by-catch due to slow growth and low reproductive rates (Dulvy and others, 2021). Recent trends do not indicate major recoveries (Juan-Jordá and others, 2022) and many shark species are threatened with extinction, with three quarters of studied species being at risk (Dulvy and others, 2021).

Despite recent recoveries (Duarte and others, 2020), marine mammals in pelagic ecosystems face significant conservation challenges from human activities and climate change (see sect. 4, subchap. 4E). Key threats include by-catch, vessel collisions, plastic and noise pollution and habitat degradation that affects food availability and migratory patterns (Avila and others, 2018; Fortuna and others, 2024). Many seabird species are also in decline (BirdLife International, 2018), with invasive species, overfishing and climate change as the primary threats (Dias and others, 2019; Gimeno and others, 2024; Sydeman and others, 2021) (see chap. 4, subchap. 4G). The pelagic phase of marine turtles is largely understudied (Robinson and others, 2023) and while many populations are declining, a few are increasing (Hays and others, 2024) (see sect. 4, subchap. 4F).

Effects of changes for humans

Catches from wild-capture fisheries have remained at around 90 million tons per year since the 1980s (FAO, 2024), while commercial fisheries now cover nearly all pelagic ocean areas (Rousseau and others, 2024) (see subsect. 5A, subchaps. 1A and 1B). This expansion may obscure warming-induced shifts in species richness from equatorial waters since the 1970s (Chust and others, 2024). With global demand for marine protein expected to double by 2050, pressure on pelagic ecosystems will likely increase and move northwards (Cruz and others, 2024).

The blue economy is projected to grow to $3 trillion annually by 2030 (Jolly, 2016), while facing challenges due to insufficient ocean knowledge (Narwal and others, 2024). It heavily relies on fisheries, with small pelagic fish and tuna comprising a significant portion of catches (FAO, 2024). Intensive fisheries management has generally improved abundance of several stocks (Hilborn and others, 2020). However, increased interest in exploiting deeper waters could jeopardize essential species, leading to declines in biomass and diversity (Ariza and others, 2022; Eduardo and others, 2024; Lin and others, 2023).

Pelagic ecosystems suffer from accumulated pollutants, particularly persistent ones like polychlorinated biphenyls and per- and polyfluoroalkyl substances (PFAS), which do not decompose naturally and cause carcinogenesis, teratogenesis and endocrine disruption (Worm and others, 2017). Nanoplastics and microplastics are of concern, contaminating marine organisms and posing health risks to humans as they bioaccumulate in the food web (Fauvelle and others, 2021; Sala and others, 2022). Risks to the open ocean include light and noise pollution and sediment discharges from mining operations, which contain harmful particulates and chemical additives

(Christiansen and Bräger, 2023; Duarte and others, 2021). Mining plumes may impact fisheries (Van Der Grient and Drazen, 2021) and human health through the bioaccumulation of toxins.

Evolution of management and conservation

Managing the high seas is challenging because of their vast and dynamic nature and the complex impact of climate change. Regional fishery management organizations (RFMOs) play crucial roles in managing pelagic species and addressing by-catch, and they are expanding to incorporate ecosystem and climate change considerations (see subsect. 5A, subchap. 1A) (SCRS-ICCAT, 2024). Proposing marine protected areas (MPAs) in the pelagic zone faces obstacles due to species' migratory behaviour, impacts of climate change, technological gaps and enforcement difficulties. Recent technological advances have improved monitoring capabilities, although the observation of biological variables and processes still presents important challenges (see sect. 4, chap. 2).

The International Seabed Authority (ISA) is responsible for the regulation of deep-sea exploration and exploitation for minerals in areas beyond national jurisdiction but has yet to adopt a regulatory code for exploitation activities. In 2023, the Authority's Assembly adopted a road map with a view to the adoption during its thirtieth session (ISA, 2024). The full regulatory framework and time frame for ISA approval are uncertain (Pickens and others, 2024). The unprecedented geographic scale of deep-sea mining, along with new technologies and poorly understood ecosystems, complicates environmental impact assessments.

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction aims to protect marine biodiversity in international waters by area-based management tools, including MPAs, and mandate environmental impact assessments. It establishes a framework for sustainable use of ocean resources, enhancing global cooperation to manage the unique challenges of pelagic ecosystems. The Agreement was adopted on 19 June 2023 by the Intergovernmental Conference on Marine Biodiversity of Areas Beyond National Jurisdiction, convened under the auspices of the United Nations, and reached its 60 ratification threshold on 19 September 2025. The Agreement became the third implementing agreement to the United Nations Convention on the Law of the Sea, which marked a significant step in ocean conservation and governance.

4. Region-specific issues

Arctic Ocean

The Arctic is experiencing rapid climate transformations, known as Arctic Amplification (Carmack and others, 2015), fuelled by sea-ice loss and radiative feedbacks (Jenkins and Dai, 2021). Sea-ice extent has significantly declined (Ivanov, 2023) and the Barents Sea has become a "hotspot" for climate change, marked by intensified inflow of warmer, saltier Atlantic waters, known as "Atlantification", which further accelerates sea-ice loss (Skagseth and others, 2020) (see sect. 4, subchap. 5K). These changes affect biodiversity and abundance of marine communities (Gordó-Vilaseca and others, 2023, 2024). The region seems to be a sink for contaminants and litter from global sources, transported from lower latitudes (ICES, 2022).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The North Atlantic faced strong to severe marine heatwaves in the summer of 2023, causing a significant decrease in chlorophyll-*a* concentration (up to 50% to 60%) in the eastern North Atlantic, which had a notable impact on ocean productivity. A persistent cold anomaly in the subpolar gyre and low salinity along the Greenland coast, likely due to increased precipitation and ice-sheet melting, have altered the distribution of several species (mackerels, bluefin tuna, humpback whales, common eiders, great cormorants) (Josey and others, 2018). In the North Sea, warming surface waters are affecting plankton, fish and fisheries distribution, with the 0 to 200 m depth zone heavily trawled. While most commercial fish stocks are stable, seabird populations are declining and seal numbers are increasing. In the Baltic Sea, climate-driven changes are reshaping the ecosystem. While most pelagic fish stocks are increasing, with the exception of the Baltic herring, non-indigenous species (NIS) are spreading. The Baltic population of the harbour porpoise is critically endangered and presently confined to the western basin, with a dramatic population decline caused by by-catch in fishing gear, underwater noise, chemical

pollution and prey depletion.[2] Mediterranean sea-surface temperatures have shown positive anomalies (Salat and others, 2019), with February 2023 reaching a record high of 1.2°C. Rising temperatures and declining primary productivity have affected small pelagic fish, altering their distribution and reducing catches (Coll and others, 2024) and the spread of non-native pelagic species is changing the biodiversity (Zenetos and others, 2022). In the Black Sea, the situation remains poorly assessed, but some large pelagic species, like bluefin tuna and swordfish, were slowly returning before recent extreme events.

South Atlantic Ocean and wider Caribbean

The south-western Atlantic Ocean is highly vulnerable to marine heatwaves (Artana and others, 2024). These marine heatwaves contributed to massive fish mortality and toxic algal blooms in the summer of 2017 (Manta and others, 2018). Moreover, on particular occasions, marine heatwaves coincided with a severe drought in south-east Brazil such as in January 2014 (Rodrigues and others, 2019). In South Africa, management trade-offs between the conservation needs of the endangered African penguin and small pelagic purse seine fisheries have sparked intense debate and legal battles (Cochrane and others, 2024; McInnes and others, 2024).

The increase in *Sargassum* seaweed blooms (see sect. 4, subchap. 4I) is now stretching across the great Atlantic Sargassum belt from the Gulf of Mexico to the western Atlantic. These blooms are exacerbated by warmer sea temperatures and nutrients run-off from coastal areas and create hypoxic zones affecting marine species, local tourism and fisheries (Marsh and others, 2023; Robledo and others, 2021).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Warming ocean temperatures and oxygen depletion in the Indian Ocean affect pelagic species, leading to shifts in the distribution of tuna, sardines and mackerel, with species moving towards cooler southern waters (Waller and others, 2024). For example, in the Arabian Sea, low-oxygen zones are expanding, reducing habitat for pelagic organisms such as Indian mackerel and scads (Lachkar and others, 2023). The Bay of Bengal faces increased hypoxia, threatening key pelagic fish species due to changing monsoon patterns (Vidhya and others, 2022). In the Persian Gulf, the effects of climate change impact pelagic fish populations (Khalfeh Nilsaz and others, 2024).

North Pacific Ocean

This region is increasingly contaminated by microplastics (Van Sebille and others, 2015; Yu and Singh, 2023). In the western North Pacific, plankton and small pelagic fish biomass fluctuations respond to the Pacific Decadal Oscillation at a multidecadal scale. However, the sea-surface temperatures regime has been unconventional in the last decade (Kuroda and others, 2020). Despite a negative Pacific Decadal Oscillation phase around 2010, lower sea-surface temperatures were recorded in some seasons and small pelagic fish population dynamics have not followed past trends.

South Pacific Ocean

Global warming and rising sea-surface temperatures affect marine life, leading to major changes in currents and upwelling zones (Bograd and others, 2023; Sutton and others, 2024; Wang and others, 2023). These changes affect the distribution, reproduction and behaviour of many marine animals (Avila and others, 2020; Montalva and others, 2022; Peters and others, 2022). Concerns about anthropogenic stressors persist, including fisheries (Ortiz and Hermosillo-Núñez, 2024). The ubiquity of microplastics (Bakir and others, 2020; Bleszynski and Clark, 2023) and the spread of the H5N1 avian influenza virus are affecting seabirds and marine mammals (Gamarra-Toledo and others, 2023; Leguia and others, 2023; Stokstad, 2023).

Southern Ocean

Circumpolar deep water warms and CO_2 concentrations have been rising (Morley and others, 2020). Atmospheric warming and declining sea-ice extent are most pronounced around the Antarctic Peninsula (Gimeno and others, 2024) (see sect. 4, subchap. 5K). This affects the recruitment success of Antarctic krill, a keystone species (Johnston and others, 2022). While current and future physical and biogeochemical changes may increase primary production (Pinkerton and others, 2021), the food web responses will depend on zooplankton reactions to warming and acidification, affecting higher trophic levels (Johnston and others, 2022; Swadling and others, 2023).

[2] See www.ascobans.org/en/species/phocoena-phocoena.

The long history of resource exploitation, primarily driven by Antarctic krill and toothfish fisheries, remains low compared to global averages (Paolo and others, 2024). However, advancements in technology and favourable environmental conditions could increase the accessibility and pressure on these resources (Rogers and others, 2020). Climate change exacerbates these challenges (Gimeno and others, 2024), alongside rising tourism, pollution, pathogens and disturbances from invasive species (Becker and others, 2024). The growing vulnerability of marine life in the Antarctic has sparked a recent initiative aiming to strengthen humankind's duty in supporting Southern Ocean ecosystems.[3]

5. Key knowledge and capacity gaps

Gaps in key processes

Although there has been progress (Eduardo and others, 2024; Egorova and others, 2024), the mesopelagic zone remains data poor. Increased interest in deepwater ecosystems highlights their ecological significance, alongside significant knowledge gaps and rising threats. Much of the biodiversity below 1,000 m also remains undiscovered, with gaps in taxonomy (smaller organisms being less studied) and species interactions.

Little is known about species movements and ecological interactions among organisms across trophic levels and regions, hindering the understanding of species distribution, ecosystem changes and effective management and conservation effects. Understanding these interactions is crucial for advancing the comprehension of ocean ecosystems and the impact of management actions (Schaber and others, 2022). Technological advancements like in situ imaging and environmental DNA are starting to address some of these important gaps.

The cumulative impact of extreme climate events is becoming a critical research focus, particularly regarding compound events and their influence on ocean dynamics, biodiversity and human livelihoods. Moreover, these events are exacerbated by other anthropogenic impacts on ocean ecosystems, such as pollution and fishing. As the frequency and intensity of extreme events rise, it is essential to understand their effects at various spatiotemporal scales. For instance, the interplay of global warming (centennial scale), Atlantic Multidecadal Oscillation (multidecadal scale), Pacific Decadal Oscillation, and El Niño and La Niña events, along with marine heatwaves (annual scale), could intricately affect organism and community dynamics in ocean ecosystems.

The start of deep-sea mining operations may soon pose a new threat to the deep-pelagic communities of the open ocean that play a crucial role as prey for higher trophic levels and in the global biological carbon pump. Assessing the severity of this threat is challenging. Moreover, the interactive effects of multiple stressors on pelagic organisms, populations and communities (and dependencies with benthic counterparts) present a key knowledge gap that requires further research (Pinsky and others, 2020; Van de Waal and Litchman, 2020). Fisheries impacts and value chains and food nutrition with a pelagic origin are important knowledge gaps, going beyond the impacts of climate change on fish production (Heneghan and others, 2023; Van de Waal and Litchman, 2020).

Technological gaps

The pelagic domain remains among the least explored areas on Earth. There is still a critical need for enhanced observational data. Biogeochemical parameters are poorly sampled compared to physical variables. Most monitoring efforts focus on surface-level measurements, limiting understanding of the deep ocean's role in heat and carbon storage, especially below 2,000 m. Recent studies using deep Argo floats reveal that decadal heat content trends are significant in these underexplored regions (Johnson and Purkey, 2024). Gaps remain in measuring vertical ocean velocities, particularly in sub-mesoscale processes. The launch of the Surface Water and Ocean Topography satellite in December 2022 is a significant advancement (Fu and others, 2024).

Challenges remain in obtaining quantitative estimates of fish and plankton biomass. An estimated 81% of zooplankton monitoring data are either unavailable or only partially accessible (Ratnarajah and others, 2023). There is a pressing need to implement findable, accessible, interoperable and reusable data standards in pelagic data (Wilkinson and others, 2016) for biodiversity

[3] https://antarcticrights.org/.

assessments (Becker and others, 2024; Ramírez and others, 2022). Further efforts on environmental DNA techniques are needed to build reference libraries (Ratnarajah and others, 2023).

Capacity-building needs

Another challenge is about digitizing and mobilizing existing data and knowledge (Meyer and others, 2015; Rogers and others, 2022). Enhancing the collaboration in international data-sharing programmes through partnerships and capacity-building can improve marine biodiversity monitoring. Taxonomic training, especially for less-known non-vertebrate groups, should remain a priority, as the value of digitized collections depends on accurate species identifications and taxonomic completeness.

Quantitative socioecological assessments are essential for analysing pelagic systems and understanding human impacts. Socioecological models must be scientifically robust yet accessible to managers and decision makers (Heymans and others, 2020). Despite progress in quantifying marine modelling uncertainty (Rynne and others, 2025; Steenbeek and others, 2024), further development is still needed.



Ellen Cuylaerts

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Subchapter 5O
Ridges, plateaus and trenches

Key points

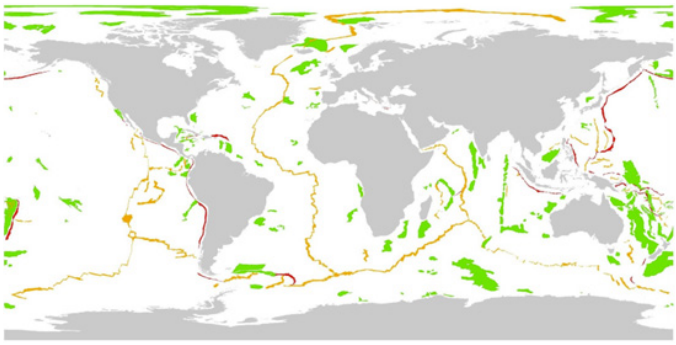
- The greatest advances have been in studies of hadal trench systems facilitated by newly available technologies.
- Progress on exploration of ridge systems has slowed, and immense gaps remain despite new discoveries in the Indian Ocean.
- Most plateaus are important fishery areas and are studied in that context.
- Changes owing to human pressures have been observed, leading to protection measures for bottom habitats (applied or are under discussion).

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1. Introduction and context

Ridges, plateaus and hadal trenches are distinctive offshore habitats, identified in the first *World Ocean Assessment* (2017) as potentially threatened by human disturbances such as fisheries, pollution and mining. In the second *World Ocean Assessment* (2021) it was reported that despite this vulnerability and added climate change pressures, they remained poorly known. The present subchapter assesses the extensive slopes of mid-ocean spreading ridges that divide ocean basins; hadal trenches at depths greater than 6000 m; and plateaus, either continent-derived fragments or other origins (see figure I). Seamounts and ridge-associated hydrothermal vents (Beaulieu and others, 2013) are considered in sect. 4, subchaps. 5L and 5P, respectively).

Figure I
World map, hadal trenches in red; mid-ocean spreading ridges in orange and plateaus in green



Source: adapted from Harris and others, 2014.

2. Description of environmental changes between 2020 and 2024

New knowledge acquired since 2020 and how it can be used to evaluate changes

Ridges

The bathyal (200 to 3,000 m depth) slopes of the mid-ocean ridge system, dominated by soft sediments interspersed with rocky outcrops at summits and fracture zones remain poorly surveyed. The Mid-Atlantic Ridge provides about half the living space for bathyal species in the North Atlantic. North of the Azores, surface productivity is high, supporting diverse demersal fish (Priede and others, 2022) and benthic invertebrates (Alt and others, 2019) with overlying waters exploited by migratory seabirds (Davies and others, 2021). Predicted seafloor biomass is lower between the Azores and the Equator, and the benthic fauna is almost unknown even in proposed deep-sea mining contract areas (26–32°N), (Radziejewska and others, 2022).

The Arctic Mid-Ocean Ridge hosts many geological features and habitat types. Although some research was done on impacts of fishing (e.g. Morrison and others, 2020), biodiversity (e.g. Ramirez-Llodra and others, 2020), mineral resources (e.g. Juliani and Ellefmo, 2018) and bioprospecting (e.g. Røyseth and others, 2023), additional studies are needed on the "typical" soft sedimentary slopes (Ramirez-Llodra and others, 2024). On the Central Indian Ridge and the South-west Indian Ridge, new species or range extensions for polychaetes, corals sponges and crustaceans were discovered (Periasamy and Ingole, 2022: Periasamy and others, 2022, 2023a, 2023b, 2023c, 2023d). The South-East Indian Ridge remains one of the least studied regions on the Indian Ocean.

No new information was published on the Pacific Oceanic Ridges.

The mid-ocean ridge system extends over 65,000 km around the globe but only in small areas around islands, seamount summits and sites of special interest such as hydrothermal vents is anything known about species, abundance, biomass and ecosystems. The Mid-Atlantic Ridge between Iceland and the Azores has been explored (Priede and others, 2022), but this represents only 5% of the global ridge system; the South Atlantic and other ocean ridges remain largely unknown.

Hadal trenches

Globally, all major hadal trenches have been surveyed with new technologies revealing a rich diversity of habitats (Weston and Jamieson, 2022; Jamieson and others, 2022). Abyssal taxa have extended into hadal depths (Jamieson and Vecchione, 2022) and new trench-endemic species and ecological relationships revealed (Lörz and others, 2018; Kniesz and others, 2018; Riehl and others, 2018; Peoples and others, 2024) with a rich hadal microbial flora including viruses (Zhou and others, 2022), bacteria (Rastelli and others, 2019) and fungi (Peng and others, 2021) that contribute to biochemical processes.

In the Indian Ocean, various habitats were observed, including soft and hard substrates in Sunda Trench (Jamieson and others, 2022). In the South Pacific, the Kermadec Trench was revisited in 2022 (Peng and Liu, 2022), revealing habitats driven by flow and substrate characteristics. Across the Pacific Trenches, seafloor biological oxygen consumption varies greatly but is always greater than on adjacent abyssal plains, reflecting increased fertilization from the rain of particles funnelled into the trenches (Glud and others, 2021).

Human impacts include accumulation of pollutants such as plastics (Abel and others, 2021), mercury (Sanei and others, 2021), halogenated organics (Cui and others, 2020) and black carbon (Zhang and others, 2022). Trench habitats are vulnerable to disturbances with estimated recovery times of over 100 years (Jamieson and others, 2022). Renewed proposals for permanent sequestration of captured liquid CO_2 into hadal trenches, which would eliminate all resident biota, are a matter for concern (Goldthorpe, 2017; Luo and others, 2023).

Plateaus

The two largest plateaus in the North Atlantic (Harris and others, 2014) are the Hatton-Rockall and Azores plateaus, both highly biodiverse and important fishery areas. The Azores plateau has interconnected assemblages of cold-water corals that differ according to the temperature and properties of surrounding waters and regional productivity (Taranto and others, 2023). It is a hotspot for large migratory marine mammals, turtles, sharks and tunas (Afonso and others, 2020), but knowledge gaps remain (Vecchione and Bergstad, 2022).

In the South-East Atlantic, mapping of vulnerable marine ecosystems of the Walvis Ridge/plateau (Bridges and others, 2023; Bergstad and others, 2019a, 2019b) shows patchy cold-water coral communities among relict coral rubble on flat-topped seamounts. In the South-West Atlantic, exploration of the summit of the Rio Grande Rise (Kitazato and others, 2017) indicated distinctive communities of corals and sponges associated with ferromanganese cobalt crusts, depth and slope (Corrêa and others, 2022; Perez and others, 2018), along with hexactinellid "sponge gardens" of *Sarostegia oculata* (Hajdu and others, 2017).

The São Paulo Plateau extends south-east from the Brazilian continental margin (2000 to 4500 m depths) encompassing over 80% of Brazilian oil and gas production (Perez and others, 2020a). In the north, asphalt seeps harbour mainly hexactinellid sponges and typical deep-sea isidid octocorals, brisingid starfishes and galatheid crabs (Fujikura and others, 2017). Along the escarpment to the south, Perez and others (2020b) described benthic habitats and communities at 4,219 to 2,644 m depths associated with topography and deep-water mass distribution.

High productivity over the plateau surrounding the Falkland Islands (Malvinas)[1] is driven by an influx of sub-Antarctic waters. Deep benthic biomass is dominated by Stylasteridae (lace corals), sponges, Pennatulacea (sea pens) and cup corals (Pearman and others, 2022).

In the southern Indian Ocean, the Kerguelen Plateau (45–65°S) traverses the Polar Front (e.g. Bestley and others, 2020), resulting in major differences in phytoplankton, zooplankton and mesopelagic fish productivity (Matsuno and others, 2020; Hunt and Swadling 2021; Cotté and others, 2022) with different trophic dynamics between the western and eastern parts of the Plateau (Hunt and others, 2021; Constable and Swadling, 2020).

In the western Indian Ocean, the Mascarene Plateau supports the largest seagrass beds in the world that, along with rhodolith beds, provide key shallow-water biogenic habitats for various taxa, including new species. Dominant mega-epifauna taxa were cnidarians, fish, echinoids and shrimps/prawns (Bhagooli and others, 2021).

Around New Zealand, benthic species distributions of the Chatham Rise and Campbell Plateau have been studied in support of habitat suitability modelling to enhance effectiveness in data-poor areas (Stephenson and others, 2021).

Unique faunal assemblages have been found on Arctic Ocean plateaus that are vulnerable to both fisheries and global warming (Jørgensen and others, 2022). In the Pacific-Arctic region, epifaunal communities of the Chukchi Plateau are proposed as long-term observatories of responses to climate changes (Zhulay and others, 2019).

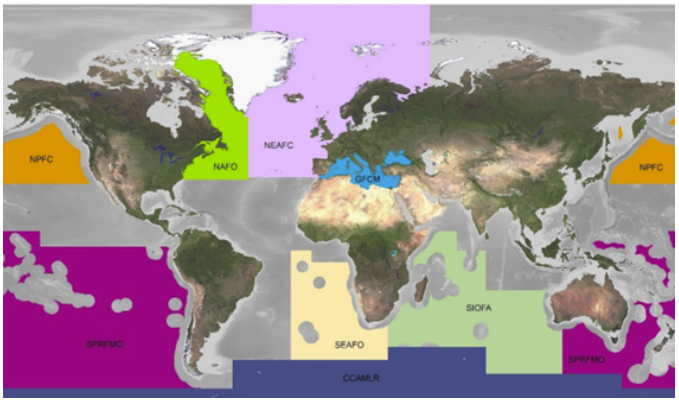
[1] A dispute exists between the Governments of Argentina and the United Kingdom of Great Britain and Northern Ireland concerning sovereignty over the Falkland Islands (Malvinas).

3. Description of economic and social changes between 2020 and 2024 and the relevant governance

Fisheries (subsect. 5A, subchap. 1A)

Deep-sea fisheries extend across slopes, seamounts, ridges and plateaus in all the world's oceans. United Nations resolutions require States to safeguard these environments either through national measures or through regional fisheries management organizations (RFMOs) (Kaikkonen and others, 2024) (see figure II). Fisheries stocks and vulnerable marine ecosystems are increasingly being protected by multiple regulations and spatial protection measures, including closed areas.

Figure II
Map of regional fisheries management organizations



Source: FAO.

Abbreviations: CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources; GFCM, General Fisheries Commission for the Mediterranean;[2] NAFO, Northwest Atlantic Fisheries Organization;[3] NEAFC, North-East Atlantic Fisheries Commission; NPFC, North Pacific Fisheries Commission; SEAFO, South East Atlantic Fisheries Organization; SIOFA, Southern Indian Ocean Fisheries Agreement; SPRFMO, South Pacific Regional Fisheries Management Organization.

In the North Atlantic, the Hatton-Rockall plateau extends across exclusive economic zones (EEZ) and areas beyond national jurisdiction and presents spatial management challenges in the face of international bottom trawling fleets (Johnson and others, 2019), whereas the Azores plateau is mainly exploited by locally based vessels managed by national measures (Morato and others, 2020). In the South-West Pacific, bottom-trawl fisheries on the Challenger Plateau are managed by New Zealand within the EEZ and by the South Pacific Regional Fisheries Management Organization in the area beyond national jurisdiction further offshore. Fisheries for hoki, ling and blue whiting on the Campbell Plateau are within the EEZ (Fisheries New Zealand, 2024).

Major trawl and bottom-set longline fisheries for Patagonian toothfish and mackerel icefish occur on some southern plateaus of the Indian Ocean, especially the Kerguelen Plateau. This has been the focus of extensive food web modelling (Subramaniam and others, 2020; Subramaniam, 2021; Hindell and others, 2022; McCormack and others, 2021).

Globally, ridge and plateau habitats are affected by marine litter largely originating from lost fishing gear (Canals and others, 2021; Duncan and others, 2023).

Mining (subsect. 5A, chap. 7)

Deep-sea mining on ridges and plateaus remains in the exploration phase under contracts issued by the International Seabed Authority (ISA) that proposes regional environmental management plans for mining areas (Blanchard and others, 2023). Please refer also to part 4 below (Region-specific changes), and to subsection 5A, chapter 7 (Mineral resources).

Climate change

The deep ocean is warming more slowly than surface waters, but analysis of shifts in expected species' range (climate velocity) indicates that deep-ocean biodiversity is highly sensitive to projected climate changes (Brito-Morales and others, 2020). Direct evidence has been recorded in the South Pacific Ocean off New Zealand where warming over the Chatham Rise is five times faster than the global rate with implications for local sustainability of fish stocks (Sutton and others, 2024).

[2] See www.fao.org/gfcm/en/.
[3] See www.nafo.int/.

4. Region-specific changes

Since 2020, several regions across the world's oceans have experienced significant environmental and human pressures, including fisheries, mineral resource exploration, climate change and pollution. In the Arctic Ocean, for example, the Chukchi Borderland plateau has been impacted by both fisheries and climate change. Protection measures such as the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean, effective since June 2021, and Norwegian regulations in the Yermak Plateau have been put in place. Similarly, in the North Atlantic Ocean, areas like the Hatton-Rockall Bank and Azores Plateau have faced fisheries pressure, with the closure of multiple regions to bottom fishing gears and the development of draft regional environmental management plans for the area. These protective actions aim to mitigate the effects of human activity, while pollution remains a significant concern.

In the South Atlantic and Indian Oceans, fisheries, mineral exploration and pollution continue to affect marine ecosystems. The South Atlantic, with regions like the Rio Grande Rise and Walvis Ridge, has seen significant protective measures, including fully protected marine protected areas (MPAs) such as Ascension Island and Tristan da Cunha, and various fishing closures across important areas like the Southern Mid-Atlantic Ridge. Brazil has also terminated cobalt crust exploration contracts in the Rio Grande Rise, claiming it as part of its extended EEZ. The Indian Ocean has seen similar pressures, with areas like the Sunda Trench and Amirante to Fortuna Banks being fully protected. Fishing closures have been enforced in regions like the Atlantis Bank and Walter's Shoal, while developments like the Central Indian Basin regional environmental management plan are being implemented to safeguard these fragile ecosystems.

In the Pacific and Southern Oceans, the situation mirrors that of the other regions, with key areas facing both human-induced and natural challenges. The North Pacific, for instance, has seen the development of a draft regional environmental management plan for the northwest Pacific, and the establishment of protected areas such as the Hawaiian Papahānaumokuākea National Monument. Meanwhile, in the South Pacific, countries like New Zealand and Australia have implemented strict protections, such as prohibiting bottom trawling along the Kermadec Ridge and creating networks of MPAs. In the Southern Ocean, the Ross Sea and South Orkney Islands are subject to comprehensive protection, with commercial fishing prohibited in specific areas. These ongoing efforts across diverse oceans emphasize the importance of international collaboration and proactive conservation strategies to address the growing pressures on marine ecosystems.

5. Key advances in knowledge and understanding

New knowledge based on advances in technology: exploration, artificial intelligence tools and the resulting implications

Knowledge of hadal trenches is being revolutionized by the advent of human-occupied vehicles capable of repeated dives to maximum ocean depth (11 km) (e.g. the United States' Deep Submergence Vehicle *Limiting Factor* and the Chinese Human Occupied Vehicle *Fendouzhe*) (Zhou and Peng, 2023). Together with autonomous landers, these have enabled global sampling programmes, the Five Deeps Expedition (Jamieson, 2020) and the Global Trench Exploration and Diving Programme to all the major trenches with detailed mapping, discovery of new species and studies of biogeological processes.

Increasing use of seafloor imagery enabled by advances in digital camera technology is providing non-destructive means of surveying the sea floor (Bell and others, 2022). Beyond the area surveyed by cameras, habitat suitability modelling can extrapolate the predicted distribution of faunal communities to data-poor areas. Off New Zealand, for example, habitat suitability maps for deep-sea corals have been developed based on seafloor imagery (Anderson and others, 2023) and modelled coral densities were used to identify areas for conservation efforts. The South Pacific Regional Fisheries Management Organization has used zonation decision-support software to help define management areas that can protect predicted vulnerable marine ecosystems habitat while permitting deep-sea commercial fishing. This analysis identified priority areas for conservation where the impact on fisheries is small (Australia-New Zealand, 2023) within the Lord Howe Rise, South Tasman Rise, Challenger Plateau and West Norfolk Ridge. Mapping at an unprecedented scale, coupled with rapidly evolving artificial intelligence, is rapidly increasing habitat suitability modelling capability. Deep learning, specifically, can both accelerate and standardize the interpretation of biological imagery data (Clark and others, 2024).

Table
Human pressures and protection measures for ridges, plateaus and trenches

Region	New data	Human pressures	Protection measures
Arctic Ocean	Chukchi Borderland plateau	Fisheries Exploration for mineral resources (chap. 7) Climate change	Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean entered into force on 25 June 2021 The Government of Norway to regulate fisheries in the Yermak Plateau, north-west of Spitsbergen/Svalbard
North Atlantic Ocean	Puerto Rico Trench Vema Fracture zone (11°N) survey Hatton-Rockall Bank Azores Plateau	Fisheries Exploration for mineral resources (chap. 7) Climate change Pollution	- Nine areas on the Hatton-Rockall Bank are closed to all bottom fishing gears (NEAFC, 2024) - Three areas between the Azores and Iceland including the Charlie-Gibbs Fracture Zone are closed to bottom fishing until 2027 (NEAFC, 2024) when they will be reviewed. - Development of Northern Mid-Atlantic Ridge draft regional environmental management plan (International Seabed Authority (ISA), 2022)
South Atlantic Ocean	Rio Grande Rise, São Paulo Plateau Walvis Ridge	Fisheries Exploration for mineral resources (chap. 7) Climate change Offshore hydrocarbons Pollution	Ascension Island and Tristan da Cunha marine protected area (MPA) - Fully protected against fishing and mining - Fishing closure areas in the Walvis Ridge (South East Atlantic Fisheries Organization) - Valdivia Bank closed to bottom trawling (SEAFO, 2015) - Six areas on the Southern Mid-Atlantic Ridge and the Wüst seamount segment of the Walvis Ridge (SEAFO, 2015) - Brazil's sponsored cobalt crust exploration contract with ISA in the Rio Grande Rise terminated. The region claimed as extended Brazilian EEZ
Indian Ocean	Sunda trench	Fisheries Exploration for mineral resources (chap. 7) Climate change Pollution	- Amirante to Fortuna Banks; fully protected Fishing closure at the Atlantis Bank of the Broken Ridge Plateau in the east and Walter's Shoal on the Madagascar Plateau in the west (SIOFA, 2024) Development of the Central Indian Basin and western Indian Ocean ridge systems regional environmental management plan (ISA, 2023)
North Pacific Ocean	Northwest Hawaiian Ridge Mariana Trench Emperor Trough	Fisheries Exploration for mineral resources (chap. 7) Climate change Pollution Concentrations of discarded cables from scientific expeditions to the Mariana Trench	Development of north-west Pacific Ocean draft regional environmental management plans (ISA, 2024) Northwest Hawaiian Ridge protected as part of the United States of America EEZ, Hawaiian Papahānaumokuākea National Monument Fishery targeting North Pacific armorhead *Pentaceros wheeleri* and splendid alfonsino *Beryx splendens* is managed by the North Pacific Fishery Commission (NPFC)

Region	New data	Human pressures	Protection measures
South Pacific Ocean	East and West Pacific Trenches	Fisheries Exploration for mineral resources (chap. 7) Climate change Pollution	- Palau MPA - fully protected - Coco Islands and Christmas Islands MPA. - fully protected - Cook Islands Marae Moana management zones, 50 km exclusion zones around the islands for deep-sea mineral exploration - New Zealand, no bottom trawling allowed along the Kermadec Ridge and complete protection 12 miles around each island on the ridge - Australia, a network of marine parks offshore where uses are managed, including areas closed to fishing - South Pacific Regional Fisheries Management Organization spatial management planning includes the Challenger Plateau, Lord Howe Rise and West Norfolk Ridge - Bottom trawling prohibited in areas of the Tasman Rise, Lord Howe Rise, Challenger Plateau and Norfolk Ridge (SPRFMO, 2023) - Bottom trawling prohibited on part of the Three Kings Ridge (SPRFMO, 2023)
Southern Ocean	East Scotia Ridge South Sandwich Trench	Fisheries Climate change Pollution	Ross Sea MPA. General protection zones where no fishing is allowed - The Ross Sea region MPA prohibits all commercial fishing on the Antarctic Continental shelf and slope and on a segment of the Pacific Antarctic Ridge (CCAMLR, 2023) In the Southern Ocean, all commercial fishing prohibited in the South Orkney Islands Southern Shelf MPA (CCAMLR, 2023)

Source: Prepared by the writing team.

6. Key remaining knowledge and capacity gaps and new gaps

Despite progress since the publication of the first *World Ocean Assessment*, gaps remain and research on ridges continues to be focused on chemosynthetic environments, seamounts and deep-sea mining, neglecting the wider ridge environment so that most of the global ridge system remains poorly known, in particular in the Arctic which is inaccessible for most of the year. Plateaus in active fishing areas are well surveyed, but no new research has been done on plateaus in the Arctic. Deep-sea ecosystems include slow-growing, long-lived and late reproducing species, making them particularly vulnerable to anthropogenic impacts yet individual and cumulative effects remain poorly known.

Management of ridges, plateaus and trenches in areas beyond national jurisdiction exists for fisheries and mining under RFMOs and the ISA. The new Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction may provide additional biodiversity protection and potential solutions for conflicts.

Sampling the deep sea requires access to large ships and advanced technologies available only in a few institutions in a few nations. This creates a lack of equitability in access and the problem of parachute, colonial or parasitic science whereby highly resourced agencies extract samples and data from poorer regions with no reference to local populations or their expertise (Stefanoudis and others, 2021), which needs to be addressed urgently. Collaborative networks developing low-cost deep-sea imaging systems that can be used from small indigenous fishing vessels may overcome some of these problems (Bell and others, 2022).

Human pressures on these high-seas ecosystems continue. Calls for capacity-development and knowledge transfer get louder (including in international agreements such as the Kunming-Montreal Global Biodiversity Framework and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction), but their targets are still far from being achieved.

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Subchapter 5P
Hydrothermal vents and cold seeps

Key points

- Discovery of new sites, novel habitats, new species and new chemosynthetic symbioses continues at a rapid pace for vents and seeps.
- Pressures are growing from climate change, fisheries and seabed mining, but protection for vents and seeps remains limited.
- New recognition, quantification and valuation of critical ecosystem services provided by vents and seeps heighten conservation imperatives.
- Inequities remain in knowledge and capacity transfer, particularly for Indigenous Peoples and low- and middle-income countries.

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1. Introduction and context

Summary of baseline state provided by the first and second *World Ocean Assessment*

Hydrothermal vents and cold seeps host high microbial and animal biomass supported by chemosynthesis, involving microbe-animal symbioses, and contribute to broader productivity and fisheries in surrounding systems. They occur at mid-ocean ridges, volcanic arcs and hotspot-associated volcanic intraplate and back-arc spreading centres (vents) and on passive continental margins and subduction zones (seeps). Both vents and seeps exhibit high spatial and temporal variability of constraining environmental factors imposing physiological adaptations. Late successional systems including cold-water corals and inactive sulfide communities may persist over centuries. The high levels of endemism provide significant species discovery and provide model systems for understanding adaptation to extreme conditions and critical climate regulating services, as well as biotechnology and biomedical potential (e.g. Bruno and others, 2019).

Technological advances have enabled discovery of thousands of sites in recent decades, as well as development of deep oil, gas and gas hydrate activities (seeps), and new mining exploration contracts (vents) issued in the Atlantic and Indian Oceans. Additional pressures include global warming, deoxygenation, ocean acidification and altered circulation, deep-sea fishing, waste dumping and plastic debris. There is growing recognition of the need for vent and seep protection. Conservation actions to date include scientific and industry codes of conduct, protected areas and International Union for the Conservation of Nature and Natural Resources Red List designations (Le Bris and others, 2017, 2021).

Scope of the coverage

Recent regional exploration and discovery of vents and seeps are synthesized below, as well as key advances in knowledge and understanding of processes and threats, description of environmental change, social implications and knowledge and capacity gaps.

2. Environmental change since the second *World Ocean Assessment*

Changes in the overall status

Climate change

Rising ocean temperatures (see sect. 4, chap. 3) caused past gas hydrate destabilization (El bani Altuna and others, 2021). The flux of methane from seabed seeps to the atmosphere is increasing in the Arctic and Antarctic (Workman and others, 2024). In a warming ocean, present-day connectivity pathways may be disrupted due to shorter larval duration (thus smaller dispersal distance) and vertical position shifts (Rakka and others, 2021), changing current patterns (magnitude or direction) (Levin and others, 2020) or loss of suitable habitat (Morato and others, 2020).

Resource exploration and exploitation

Intense research occurs at some vent sites with likely impacts (Juniper and others, 2019). Recovery from a small, induced disturbance at a Mid-Atlantic Ridge vent found altered community structure after two years, with implications for deep-sea mining (Marticorena and others, 2021). As of 2024, the International Seabed Authority (ISA) has signed seven exploration contracts for vent deposits in the Atlantic and Pacific Oceans (see subsect. 5A, chap. 7). Exploration licences are active in Japan, Tonga and Papua New Guinea, while Norway has initiated approvals. Exploitation of active vents may cause losses of species, functions and connectivity (Alfaro-Lucas and others, 2024; Tunnicliffe and others, 2024), while knowledge of the ecological value of inactive/extinct sulfides is limited (Van Dover and others, 2020). Offshore oil and gas development continues (see subsect. 5A, subchap. 3B), likely affecting associated methane seeps.

Bottom trawling (see subsect. 5A, subchap. 1C) exerts pressure on cold seep faunas, as commercial species often congregate near seeps (e.g. Sen and others, 2019; Turner and others, 2020). Foundation species were reduced at New Zealand seeps (Jones, 2023) and trawl nets were tangled on carbonates on the Canadian Pacific Margin (DFO, 2018). In Norway, broken carbonates and trawl marks had limited recolonization (Bellec and others, 2024). Hydrocarbon exploration on continental margins (see subsect. 5A, subchap. 3B) has located methane seep communities (e.g. Dueñas and others, 2021; Bravo and others, 2024). Extraction will likely diminish the

methane supply that fuels chemosynthesis as observed by Boles and others (2023).

Factors contributing to the change observed

The changes are driven by rising populations and industry development increasing fishing pressure (see subsect. 5A, subchap. 1C), energy demand (see subsect. 5A, subchap. 3B) and emissions (causing warming) (see sect. 4, chap. 3), as well as rising metal demand and geostrategic contexts (see subsect. 5A, chap. 7), in part for electrification of transport.

Impacts and interactions of the change with other marine system components

Discoveries of large nursery areas of deep-sea species near vents and seeps (e.g. Barry and others, 2023) suggest that changes in these systems can influence recruitment to non-vent species, including from higher trophic levels.

Social, economic and cultural aspects associated with the change (since the second *World Ocean Assessment*)

As potential exploitation draws closer, societal awareness is growing, often with strong disagreements with State or ISA actions (e.g. van Putten and others, 2023; Gilbert, 2024). Mining at vents may intersect with sites of cultural heritage significance (Turner and others, 2020) (see subsect. 5B, chap. 5).

Implications for the 2030 Agenda for Sustainable Development and for the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction

Protection supports Sustainable Development Goal 14 through sustainable management (target 14.2) and strengthening resilience using marine protection areas (MPAs) (target 14.5). ISA (ISBA/27/C/8) declares support for Goal 14 through its regulatory framework for seabed mining, which requires trade-offs with Goal 7 (energy) and Goal 8 (industry). A draft regional environmental management plan (ISBA/27/C/38) reflects target 14.2 by classifying active hydrothermal vents as needing protection. Current mining code development aims to prevent environmental harm while mining in vent areas. Protection of vents and seeps, plus the ecosystem functions and services they provide, can help meet the Kunming-Montreal Global Biodiversity Framework targets. For the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, all four components are relevant.

3. Region-specific changes: new discoveries and new pressures

The figure depicts previously known and recently discovered (since 2018) deep vents and seeps.

At shallow vents and seeps (less than 200 m; not mapped in the figure), species may coexist alongside photosynthetic algae and seagrass, and have greater exposure to anthropogenic changes including warming, ocean acidification, bottom fishing, pollution or invasive species (Ramirez-Llodra and others, 2010; Åström and others, 2018). New technologies were increasingly used for analysing deep-sea biota, revealing magnificent vent assemblages (e.g. Gerdes and others, 2021; Ramirez-Llodra and others, 2024; Sun and others, 2020). Vent and seep faunas show heterogeneity linked to depth, surface production, oxygen minimum zones and geology (Seabrook and others, 2024).

Arctic Ocean

First found in the 1990s, cold seep discovery continues in the Arctic (e.g. Waghorn and others, 2022; Sen and others, 2019; Serov and others, 2024), as well as two recently discovered vent fields (Stensland and others, 2019; Sahlström and others, 2023) and many new vent species (Eilertsen and others, 2024) (see sect. 4, subchap. 5O).

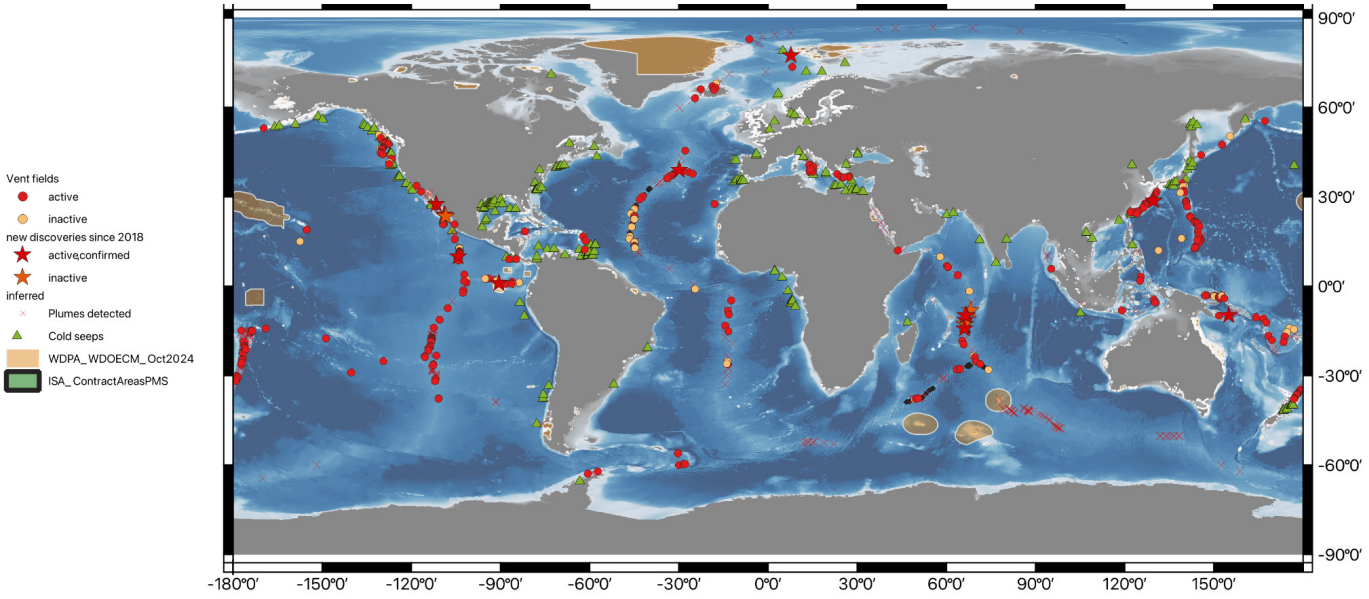
North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

New vents were discovered on the Mid-Atlantic Ridge (Butterfield and others, 2023). Other new vents discovered south of Iceland at the Reykjanes Ridge were noticeably lacking typical vent macrofauna (Taylor and others, 2021). In the North-West Atlantic margin,

acoustic imaging revealed approximately 1,139 unique methane flare sites; most are shallower than 400 m, but some extend to 1400 m (Ruppel and others, 2024). A newly discovered squat lobster in the Gulf of Mexico is the first west Atlantic seep endemic (Rodriguez-Flores and others, 2024).

Figure

Global map of confirmed active (red symbols) or reported inactive vent fields (orange symbols) and cold seeps (green triangles); for vents, stars denote vent fields discovered in 2018–2024; brown polygons represent designated marine protected areas



Sources: Vent field locations are from the InterRidge Vent Database (Beaulieu and Szanfranski, 2020) completed by recent references (Zhou and others, 2018; Soule and others, 2018; Paduan and others, 2018; Ryu and others, 2019; Jang and others, 2023; Boulart and others, 2022; McDermott and others, 2022; Bohrmann and others, 2022; Zhou and others, 2022; Chen and others, 2024; Dang and others, 2024; Lecoeuvre and others, 2021). Seep site data listed in the Biogeography of Deep-Water Chemosynthetic Ecosystems Database (ChEssBase, 2019) were completed from other inventories (Olu and others, 2010; Quattrini and others, 2015; Baumberger and others, 2018; Feng and others, 2018; Etiope and others, 2019; MacDonald and others, 2020; Aguilar Pérez and others, 2024).

Note: MPAs are taken from Protected Planet: The World Database on Protected Areas and World Database on Other Effective Area-based Conservation Measures: UNEP-WCMC and IUCN, 2024. Bathymetry is the GEBCO One Minute Grid map from www.gebco.net/data_and_products/gridded_bathymetry_data/. This map was built using QGIS 2.18.20.

South Atlantic Ocean and wider Caribbean

Seeps in the West Atlantic, the Caribbean and off Colombia are associated with linear diapir systems, salt diapirs resulting from salt tectonics, regions of mud volcanism and compact seafloor mounds; most knowledge is still associated with the oil and gas industry, with limited access to the science community and limited faunal studies (Aguilar Pérez and others, 2024). Argentina's first methane seeps (approximately 500 m) are reported with dense infaunal assemblages (Bravo and others, 2024).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

New discoveries include a rare serpentinite-hosted field (Lecoeuvre and others, 2021) and the first actively diffusing vent system in the Red Sea (Van der Zwan and others, 2023); both host unique microbial communities without typical vent macrofauna. Faunal studies described over 30 new taxa and indicate within-region biogeographic discontinuity (e.g. Jang and others, 2023). Two new seep communities were reported in the northern Indian Ocean with biogeographic affiliations with the West Pacific vent/seep communities (Mazumdar and others, 2019), and a new active cold seep site occurs in the Bay of Bengal (Sangodkar and others, 2023).

North Pacific Ocean

Serpentine-hosted seep communities at mud volcanoes on the Mariana Forearc, where methane-rich fluids are highly alkaline (pH over 12), support many novel species (Chen and others, 2023, 2024a) (see sect. 4, subchap. 5L). New North-East Pacific Ocean vent and seep sites continue to be discovered (Galkin and others, 2019) notably including 1,600 methane flares mapped in the Canadian Pacific (DFO, 2018) and eight new seeps off the coast in Oregon and Washington (Seabrook and others, 2024). Low-temperature ridge-flank hydrothermal springs in the North-East Pacific Ocean support deep-sea octopus nurseries (Barry and others, 2023).

South Pacific Ocean and equatorial Pacific Ocean

A newly discovered vent site in the South-West Pacific may contribute to faunal connectivity (Boulart and others, 2022). Other new vent sites in the Galapagos Rift expand the records of vent species (Chen and others, 2024b).

Southern Ocean

Three new deep-sea vent sites have been reported in the Atlantic region of the Southern Ocean (Bohrmann 2019; Linse and others, 2022). Major new seepage sites in the Ross Sea indicate likely widespread climate-sensitive phenomena around Antarctica (Seabrook and others, 2023).

4. Key remaining knowledge and capacity gaps and new gaps

Advances in technology

Many technological advances have improved understanding of chemosynthetic ecosystems, such as (i) evolving molecular tools to support systematics and studies of adaptations to extreme environments and genetic connectivity (e.g. Zeng and others, 2020); (ii) photogrammetry methods for 3D reconstructions to aid habitat change studies (e.g. Van Audenhaege and others, 2024); (iii) neural network approaches to image classification (Vega and others, 2024); and, (iv) novel computer algorithms for seep identification (Vrolijk and others, 2021; Ruppel and others, 2024).

Novel habitats and processes

Important new findings include subseafloor vent faunal habitats (Bright and others, 2024) and off-axis hydrothermalism (McDermott and others, 2022; Parsons and others, 2024), novel chemo-symbioses (Goffredi and others, 2020, 2021) and inactive vent species (Chen and others, 2024a). Microbial processes are implicated in primary productivity at inactive vent deposits (Achberger and others, 2024), in carbon cycling and nutrient export (Versteegh and others, 2023) and in trophic networks in vent communities (Murdock and others, 2021). A comprehensive genomic catalogue of microbes from seeps (Han and others, 2023) enables exploration of functional processes such as biogeochemical cycling.

Dynamics, succession and sphere of influence

Long-term observations and experiments reveal high stability and slow recovery of vent ecosystems in slow-spreading ridges following disturbance (Van Audenhaege and others, 2022; Marticorena and others, 2021). Evidence that vents and seeps affect the ocean outside their perimeters accumulates, such as iron from rising vent plumes inducing phytoplankton blooms in the Southern Ocean (Ardyna and others, 2019) and enhanced faunal abundance on the seafloor (Klunder and others, 2020). At seeps, input from both chemosynthesis and photosynthesis support distinctive infaunal communities in an intermediate zone between methane seeps and background (Ashford and others, 2021).

Stepping stones

Population connectivity could enhance resilience to disturbance. Highly divergent gene flow directions and ranges exist among closely allied vent species (e.g. Breusing and others, 2023; Methou and others, 2024). A novel, but isolated, Arctic vent ecosystem in a region with imminent mineral exploration provides evidence for historical connectivity (Eilertsen and others, 2024). Range analyses divide the Indian Ocean into three vent provinces that suggest separate management areas (Zhou and others, 2022). In the North-West Pacific Ocean, the Okinawa Trough has high endemicity (Brunner and others, 2022) while connectivity along the volcanic arcs appears limited for many species (Giguère and Tunnicliffe, 2021). Most vent species are known only within one limited region; for a few species, the Manus Basin is the key region for cross-equator linkages (Brunner and others, 2022; Tunnicliffe and others, 2024). At both vents and seeps, some widespread species form localized genetic units with rare long-distance dispersal events (Jollivet and others, 2024).

Ecosystem services

Hydrothermal vents provide regulating services such as biogeochemical cycling of manganese, iron and nitrogen and carbon fixation. Provisioning services include marine genetic resources (e.g. Fuelzyme; see Bravakos and others, 2021; Giordano, 2020) (see subsect. 5A, chap. 5) and potential metals from mining (see subsect. 5A, chap. 7). Supporting services include nutrient transfers to deep-sea and nursery areas at both active and inactive vents. Cultural values flow from scientific research (e.g. models for extraterrestrial life) and creative inspiration (DOSI, 2023). Cold seeps provide provisioning services through commercial fish/crustacean species and regulating services through carbon sequestration (Le and others, 2022). This new understanding heightens conservation imperatives.

Consequences of environmental impacts, governance challenges, conservation status

About half of known vent sites fall in areas beyond national jurisdiction where many are under mining exploration contracts; regulations on the conservation status of vents within contract areas are under development. Of all other vents, 17% are covered by non-targeted conservation interventions while 8% benefit from vent-specific actions (Menini and others, 2023). For new and updated areas, see the table. Four South-West Pacific States initially declared a moratorium on deep-sea mining (Melanesian Spearhead Group (MSG) Secretariat, 2020); today 32 States have taken a position against deep seabed mining in international waters. Thomas and others (2021) find the limited distribution of most vent molluscs is the key vulnerability, with notable extinction threat in mining contract areas. However, regular distribution assessment updates are needed. Conservation is in place for very few cold seeps although many are vulnerable to anthropogenic disturbance and climate change (Le and others, 2022; Bellec and others, 2024). An economic valuation identified highest willingness to pay to conserve Costa Rican seeps with endemic species (Pereira and others, 2024). Governance in the areas beyond national jurisdiction is problematic due to fragmented and variable approaches (Menini and others, 2023), and protections remain limited.

Key remaining knowledge gaps

Many knowledge gaps identified in the second *World Ocean Assessment* (Le Bris and others, 2021) remain, including the distribution, biogeography and connectivity of vent and seep biota, resilience and time and space scales of recovery from disturbance (trawling, mining, climate change) and vent and seep roles in biogeochemical cycles. Capacity gaps are being identified (Bell and others, 2023) and addressed (Johannes and others, 2023), but limited access to funding, research vessels, low-cost instruments and taxonomic expertise remain, creating global inequity. Small island developing States, for example, although often in close proximity, have limited access to hydrothermal vents and seeps. Currently several international programmes offer training opportunities, and philanthropic foundations offer some research vessel support.

Newly recognized knowledge gaps

Regional gaps in location of new sites and in novel habitats, functions, symbioses and other mutualistic interactions among species, and genetic resource potential at vents and seeps exist. Additional key gaps include vent-seep-organic fall connectivity and stepping-stone functions including the role of inactive and ecotone/transition vent (Boschen and Colaco, 2021; Neufeld and others, 2022) and seep (Pereira and others, 2021) sites, and animal-microbe interactions at active vents (Murdock and others, 2021), seeps (Pereira, 2024) and inactive sites.

Table

Emerging threats, risks and conservation measures since 2019

Basin	Threat actions	Other risks	Conservation measures	Citations
Arctic	Norway approved (but paused in Dec. 2024) exploration for extraction of polymetallic sulfides	Warming waters could bring colonists to seeps and vents northward challenging endemic species		Delivorias, A., 2024. Åström, E.K. and others, 2020
North Atlantic and Mediterranean	Exploration of three ISA contract areas in progress in active vent sites	Bottom-contact fishing on shallower vent areas Marine litter (mostly plastics) in vent habitats from abandoned fishing gear	Luso hydrothermal field MPA in Portugal ISA considers regional environmental management plan proposal to protect all active vents from mining in contract areas	Governo dos Açores, 2022 International Seabed Authority, 2022 Consoli, P. and others, 2021
Western tropical Atlantic and Caribbean		Submarine slides caused by methane hydrate destabilization in a warming ocean Lack of literacy and capacity to address impacts		Ruffine, L. and others, 2023 Amon D. and others, 2022
South Atlantic	Oil and gas exploration in deep water continues off Argentina near newly discovered seeps		Ascension Island MPA (United Kingdom) Covers 750 km of ridge crest with known vent sites	Ascension Island Government, 2021 Bravo M. and others, 2024
North-East Pacific	Notable climate-induced deoxygenation in the MPA (Ross and others, 2020) may affect shallow vents and larvae	Bottom-contact fishing on shallower vent areas Deep seabed mining could affect vents	Tang.ɢwan – ḥačxʷiqak – Tsig̱is MPA now including all confirmed hydrothermal vents in Canada and some methane seeps	Canada Gazette, 2024 Ross, T. and others, 2020
North-West Pacific		Microplastic accumulation in cold seep animals	Northern part of Central (Naka) Mariana Ridge and West Mariana Ridge MPA (Japan) Includes three vent sites	Teng, J. and others, 2023 Watanabe H.K. and Yamakita T, 2022 Government of Japan, 2020
South-West Pacific	Potential renewal of seabed exploitation licence for polymetallic sulfides at Solwara, Manus Basin, Papua New Guinea			Monga Bay, 2024
Indian Ocean	Exploration of four ISA mining contract areas in progress at active vent sites	Microplastic accumulation in vent animals		Park, B. and others, 2024
Global	Seabed mining	Ocean warming and acidification	Assessment of hydrothermal vent species against the International Union for Conservation of Nature (IUCN) and Natural Resources Red List criteria. Of these, 114 fall into the Vulnerable, Endangered or Critically Endangered categories.	Thomas, E.A. and others, 2021

Source: Prepared by the writing team.

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Subchapter 5Q Sargasso Sea

Key points

- The Sargasso Sea is an iconic high-seas ecosystem internationally recognized as a fundamentally important part of the global ocean.
- The Sargasso Sea has been consistently identified as an area of the high seas that would benefit from international legally binding protection (IUCN, 2008; UNESCO, 2016). The adoption of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction on 19 June 2023 (A/CONF.232/2023/4) provides an opportunity to further this ambition.
- *Sargassum* continues to inundate beaches in more southern latitudes and new research suggests these blooms are driven by anthropogenic nutrient inputs into the system.
- The first satellite-tagging evidence of the European eel migrating to the Sargasso Sea emphasizes the importance of the area for these economically important fish. An increased understanding of the ecology of commercial tuna and tuna-like species and awareness of the use of the area by endangered and threatened species are increasing the need for an ecosystem approach to fisheries management.
- Ship traffic has increased on the Sargasso Sea over time and de facto shipping routes have been established by shipping companies. This increased traffic may carry risks to cetaceans of collisions and noise pollution.
- The increasing activity in the Sargasso Sea demonstrates the importance of addressing the cumulative impacts of human activities on the high seas.

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1. Introduction and context

The present subchapter builds on developments and knowledge of the previous baseline state as reported in chapter 50 of the first *World Ocean Assessment* and chapter 7Q of the second *World Ocean Assessment* and summarized in this part of the subchapter. The oceanography of the Sargasso Sea within the North Atlantic Gyre is well understood from two of the longest-running time series of oceanographic data, Hydrostation S and the Bermuda Atlantic Time-series Study.

The Sargasso Sea supports a unique surface ecosystem based upon floating aggregations of two species of *Sargassum (S. natans* and *S. fluitans)* and their role as feeding and nursery areas for pelagic fishes, juvenile turtles (see subchap. 4F) and seabirds (see subchap. 4G). The Sargasso Sea is the only known spawning area for the European eel (*Anguilla anguilla*) and the American eel (*Anguilla rostrata*). The Sargasso Sea acts as a migratory corridor for several species of sharks, rays, turtles and cetaceans. A number of species inhabiting the Sargasso Sea are endangered or threatened.

The Sargasso Sea remains a fundamentally important part of the global ocean due to the ecosystems it supports and its role in global-scale ocean processes, particularly in carbon sequestration. It contributes significantly to local as well as global economies both directly from fisheries for highly migratory species (tunas, swordfish) and harvesting of Anguillid eels, whale and turtle tourism, and indirectly from its role in climate regulation, conservation of genetic diversity and nutrient cycling (Laffoley and others, 2011; Pendleton and others, 2014). It is threatened by climate change, pollution, increased fishing effort and international shipping.

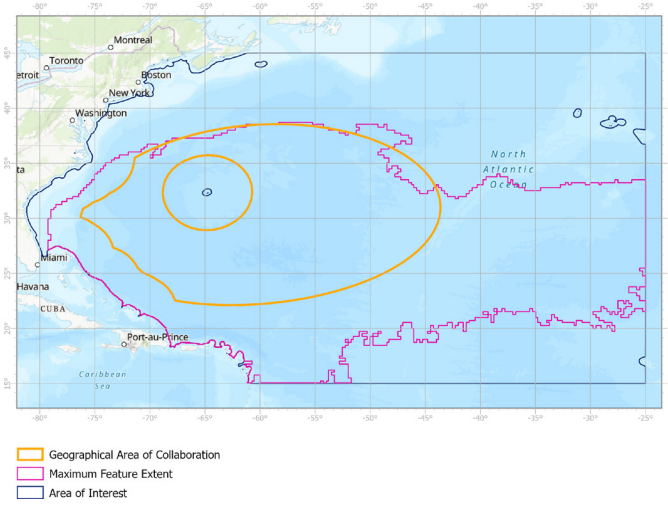
The conservation work of the Sargasso Sea project began in 2010, but it has been boosted recently by two major grants: the Global Environment Facility–United Nations Development Programme–Intergovernmental Oceanographic Commission project (under the Food and Agriculture Organization of the United Nations (FAO) Common Oceans Programme) on "Strengthening the stewardship of an economically and biologically significant high seas area – the Sargasso Sea", and the French Facility for Global Environment SARGADOM project are financing a socioecosystem diagnostic analysis that underpins this subchapter. In addition, the significance of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction is outlined, including its impact on the conservation of the Sargasso Sea.

2. Environmental change since the second *World Ocean Assessment*

Location

The Sargasso Sea is a pelagic ecosystem bounded by the currents of the North Atlantic Gyre. The Sargasso Sea Commission acts as steward of the ecosystem under an area of collaboration defined in the 2014 Hamilton Declaration. New work from the Duke University Marine Geospatial Ecology Laboratory emphasizes the dynamic nature of the Sargasso Sea, represented by a "maximum feature extent" with shared biogeographical characteristics (Cleary and others, 2023) (see figure I).

Figure I
Sargasso Sea maximum feature extent



Source: Smith and others, 2023.

Note: For more information on how the figure was created, see Cleary and others, 2023; and Smith and others, 2023.

Ocean time series

Continued monitoring of the Sargasso Sea from Hydrostation S and the Bermuda Atlantic Time-series Study (which are long-standing ocean quality monitoring sites) has shown that the last 40 years have seen significant surface ocean warming of approximately 1.2°C, lengthening of summertime conditions and shortening of wintertime conditions, slowdown of subtropical mode water formation, salinification due to reorganization of the global water cycle and uptake of anthropogenic carbon dioxide (CO_2) such that ocean acidification levels in the 2020s of the Sargasso Sea are outside the range observed in the 1980s and before (Bates and Johnson, 2020, 2023; Stevens and others, 2020). Marine photosynthesis has also changed with knock-on effects for the higher trophic level ecology of the Sargasso Sea (Lomas and others, 2022) and the marine ecosystem may have also changed in concert with these physical changes (Bates and others, 2023).

In terms of chemical oceanography, since the late 1980s, waters in this subtropical region of the North Atlantic Ocean have lost oxygen at a rate of approximately 2% per decade (approximately 8% over the past 40 years) (Bates and Johnson, 2020, 2023). From the early 2000s to the present, rates of primary production have decreased by more than 25% (Lomas and others, 2022; D'Alelio and others, 2020). Notably, over the past several decades, carbon export to the deep ocean has remained steady while primary production has decreased (Lomas and others, 2022) with significant changes in ecosystem community structure (Bates and others, 2023).

Sargassum

Increased sea-surface temperature has implications for the *Sargassum* ecosystem (for additional information on algae, see sect. 4, subchap. 4I). Graba-Landry and others (2020) showed that elevated temperature impacts the survival of a *Sargassum* algae (*S. swartsii*) and while it remains to be seen specifically how temperature impacts the two dominant *Sargassum* species of the Sargasso Sea, warming patterns revealed in the analyses suggest broader implications for the integrity of *Sargassum* mats (Graba-Landry and others, 2020).

Although *Sargassum* supports a thriving ecosystem in the Sargasso Sea, it has economic and ecological impacts when it inundates beaches, as discussed in the chapters on this topic in the first and second World Ocean Assessments. Blooms of *Sargassum* in the North Equatorial Recirculation Region are hypothesized to be linked to anthropogenic nutrient inputs into the ocean through the Orinoco and Amazon Rivers, and anthropogenic climate change (McGillicuddy and others, 2023).

Sargassum in the North Equatorial Recirculation Region is morphologically different from the *Sargassum* in the Sargasso Sea (Alleyne and others, 2023). *S. natans I* and *S. fluitans III* are the most predominant variations in the Sargasso Sea, while *S. natans VIII* is the most predominant in the North Equatorial Recirculation Region and this morphological type has also been found to support a less diverse rafting community (Schell and others, 2015), which could threaten the Sargasso Sea if *S. natans VIII* eventually invades a more northern area.

Fisheries

The first direct evidence of European eel migration to the Sargasso Sea using satellite tags was published in 2022 (Wright and others). Interest in the conservation and sustainable management of the species continues to grow due to its economic importance for human consumption (for broad information on medium and large-scale fisheries, see subsect. 5A, subchap. 1A).

The western central Atlantic Ocean is among the least fished FAO major marine fishing areas in the world (see figure II). The landing volume and value in this portion of the high seas since 2010 have remained relatively low and stable, where catches consist of large pelagic species, primarily albacore tuna, swordfish and blue sharks. The Sargasso Sea only represents 0.47% of the volume of fisheries catches across the International Convention for the Conservation of Atlantic Tuna convention area (Vousden and others, forthcoming).

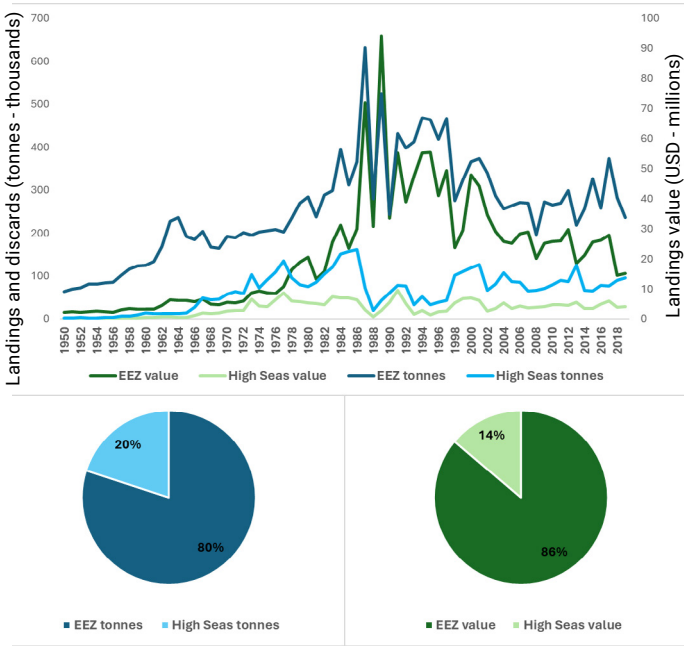
The United States Atlantic pelagic longline fleet generated around $10 million in profit without subsidies. However, without subsidies, the Spanish pelagic longline fleet would have lost between $1.5 million and $2.78 million, and the other fleets would have lost between $4.49 million and $7.25 million a year.

The majority of fishing in the Sargasso Sea seems to be unprofitable without subsidies. The Subtropical Convergence Zone, where warm and cold-water masses meet, occurs between 22°N and 30°N in the southern sector of the Sargasso Sea and has been shown to be a significant seasonal spawning area for three species (albacore tuna, swordfish and white marlin) managed by the International Commission for the Conservation of Atlantic Tunas

(Luckhurst and Arocha, 2015), and important areas for the reproductive cycle of the blue marlin and porbeagle shark (Luckhurst and others, 2006; Campana and others, 2010). The first record of eggs and juveniles of the rare roundscale spearfish in the Sargasso Sea was reported by Freese and others in January 2025.

Figure II

Fisheries landings volume and value in FAO fishing area 31 across the high seas and the exclusive economic zones (1950–2018)



Source: Sea Around Us (www.seaaroundus.org).

Deep sea

Pioneering scientific studies in the north-western margins of the Sargasso Sea have been pivotal in understanding patterns of abundance, biomass and diversity in deep-sea ecosystems. Below the epipelagic zone sampling of mesopelagic and bathypelagic communities of fish suggests they may form a single Central North Atlantic province spanning the entire Sargasso Sea (Backus and others, 1977). Benthic communities show a decline in abundance and biomass with depth (Sutton and others, 2010). Falling Sargassum affects the deep-sea ecosystem and some organisms are specially adapted to feed on this macroalgae (Peoples and others, 2024). Coral and sponge habitats on seamounts are associated with distinct communities of fish and other associated organisms.

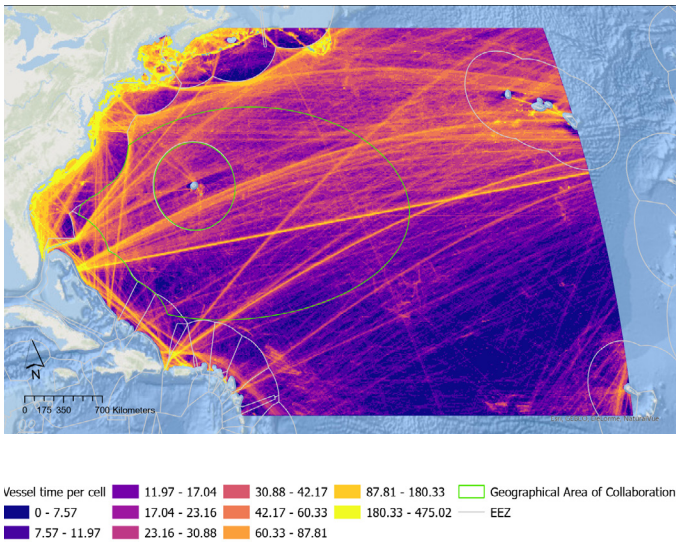
France, Poland and the Russian Federation have mining exploration contracts awarded by the International Seabed Authority (ISA) for seabed massive sulfides on the Mid-Atlantic Ridge.[1] Active vents in this region are often associated with vent-endemic fauna. The Lost City hydrothermal field is a unique hydrothermal vent system and may be of high scientific importance as the physio-chemical conditions may resemble those of the ancient Earth when genesis of life occurred (Johnson, 2019; Brazelton and others, 2022). Documentation of the species and ecology of each active vent ecosystem and surrounding non-vent ecosystems, which are currently unexplored, will be required before management plans can be designed for potential mining of any of these sites, in accordance with the draft ISA regional environmental management plan.

Shipping

Vessel traffic in the Sargasso Sea ranges from highly concentrated shipping routes across the middle North Atlantic to the less intensively occupied fishing grounds around the Gulf of Maine and the coast of Labrador (see figure III).

Figure III

Summary of vessel traffic (vessel time in hours) in 2021



Source: Smith and others, 2023.

Several corridors experiencing particularly high vessel volume can be identified consistently across time (Smith and others, 2023). Vessels transiting these major routes connect ports primarily in the United States of America,

[1] See www.isa.org.jm/exploration-contracts/.

the United Kingdom of Great Britain and Northern Ireland, Panama, the Kingdom of the Netherlands, Spain, Gibraltar and Egypt (Smith and others, 2023).

With the presence of these prominent vessel traffic lanes through the centre of the Sargasso Sea, it is important to consider the potential environmental impacts of this traffic for cetaceans, many species of which are known to migrate through the area, especially humpback whales, including effects from noise pollution and collisions (see Smith and others, 2023, and reference to important marine mammal areas below).

3. Institutional arrangements and partnerships

As outlined in the second *World Ocean Assessment*, the Sargasso Sea faces a unique challenge in its conservation: it is located in an area beyond national jurisdiction. The Sargasso Sea Commission was established pursuant to the 2014 Hamilton Declaration on Collaboration for the Conservation of the Sargasso Sea to fill this lacuna in the regime. It has 10 Government signatories[2] who pledged to work collaboratively to conserve the iconic ecosystem of the Sargasso Sea (for more information on high-seas ocean governance, see sect. 3).

The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction represents a major change in the international legal landscape for the high seas since the inception of the Sargasso Sea project in 2010. It opens up a new pathway for area-based management tools (including marine protected areas (MPAs)) for the high seas.

The United Nations Development Programme–Global Environment Facility–Intergovernmental Oceanographic Commission/French Facility for Global Environment supported socio-ecosystem diagnostic analysis for the Sargasso Sea – the first for a high-seas ecosystem – will provide the basis for a strategic action programme for the Sargasso Sea. The strategic action programme will reflect the agreement of the Sargasso Sea stakeholders on a mechanism for more effective stewardship and conservation of this unique ecosystem.

The 2011 description of the Sargasso Sea as an ecologically or biologically significant area is a scientific determination, but hopes that States and competent international organizations would utilize it to deliver conservation benefits have not materialized (Roe and others, 2022). Nevertheless, the Sargasso Sea Commission's achievements are still considerable (Freestone, 2021). In 2023, the Commission cohosted with the International Maritime Organization a workshop on particularly sensitive sea areas on the high seas, an International Maritime Organization tool designed to reduce pressures from international shipping. In 2024, it supported an International Union for Conservation of Nature (IUCN) and Natural Resources/important marine mammal area workshop resulting in the designation of an important humpback whale north-south migratory corridor across the North Atlantic as an important marine mammal area in 2025. The Convention on Migratory Species is developing a single species action plan for the European eel, in consultation with Range States and relevant intergovernmental organizations and non-governmental organizations, under the mandate from the fourteenth Conference of the Parties (Decision 14.109).[3] Under the French Facility for Global Environment SARGADOM project, the Commission is developing tools for remote monitoring of the high seas with partners, including Global Fishing Watch (Freestone and others, 2024).

4. Key remaining knowledge and capacity gaps and new gaps

Climate change and its accompanying effects of ocean acidification and changes to ocean circulation (e.g. Ditlevsen and Ditlevsen, 2023) are the impacts with the furthest-reaching consequences for the Sargasso Sea, which could fundamentally change the Sargassum ecosystem and affect the distribution of larvae and the

[2] The Azores, The Bahamas, Bermuda, the British Virgin Islands, the Cayman Islands, Canada, the Dominican Republic, Monaco, the United Kingdom of Great Britain and Northern Ireland and the United States of America.

[3] At the fourteenth session of the Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals in Samarqand, Uzbekistan, February 2024. Decision 14.109. See www.cms.int/sites/default/files/document/cms_cop14_decisions_e.pdf.

migration of fish and other species. Plastics and other pollutants are also a constant threat.

Fishing effort remains low in the Sargasso Sea, but research shows most fishing activity requires heavy subsidies to reach the area (Vousden and others, forthcoming). Anguillid eels remain economically important, but encounter most threats during the inshore stage of their life cycle.

Ship traffic has increased on the Sargasso Sea over time and de facto shipping routes have been established by shipping companies. With the risk of ship strikes to cetaceans, more research and discussion are needed on the effects of international shipping in the Sargasso Sea, and the need and feasibility of conservation measures related to international shipping in the area.

Gaps in knowledge for the area include by-catch, illegal, unreported and unregulated (IUU) fishing, movements of highly migratory species, plastics, impacts from deep-sea mining and deep-sea ecology. The cumulative impacts of all threats to the Sargasso Sea discussed are likely to combine to be greater than the sum of their parts, and the full effects of cumulative impacts are unknown.

The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction represents a seismic shift in the international regime for the high seas, with the potential to streamline the conservation of the Sargasso Sea. While area-based management tools do not necessarily protect against non-spatial threats, they can remove anthropogenic pressures on the ecosystem, providing greater resilience in a changing climate and increasing the potential for sustainable ecosystem benefits.



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Subchapter 5R
Fjord systems

Key points

- Fjords are ecologically carbon organic-rich regions and home to Indigenous Peoples and local communities.
- Global warming is already affecting both northern and southern hemisphere fjords (through warming, deoxygenation and acidification).
- The loss of glacier ice and the changing seasonality of the hydrological cycle is affecting physical and chemical factors and processes in fjord systems.

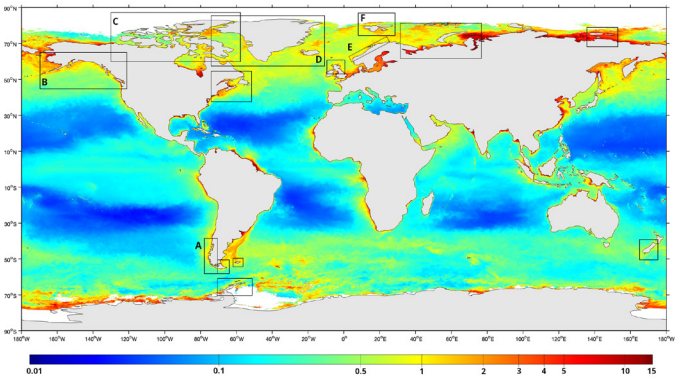
Writing team: Jose L. Iriarte (coordinating author), Ian Butler (co-lead member), Agneta Fransson, Jennifer M. Jackson, Lorenz Meire, Renato Quinones (lead member), Sofia Ribeiro and Fiammetta Straneo.

1. Introduction

The fjord systems of the world are characterized by a deep basin connecting directly or indirectly with the open sea at the mouth (Matthews and Heimdal, 1980). Fjords are often long, narrow, deep and steep-sided inlets, frequently branched and sinuous, or straight, and may contain one or more submarine sills (a shallow dome of bedrock that forms at the mouth of a fjord). The presence and size of these sills at the fjord's mouth can restrict the exchange of water between the fjord and the coastal ocean, often leading to highly stratified conditions that result in low-oxygen bottom waters. Main fjord regions occur along the coasts of North and South America (above 42° latitude); many sub-Antarctic islands; the south-west coast of New Zealand's South Island; Antarctica;[1] the Russian and Canadian Arctic Archipelagos; Svalbard, Norway;[2] Iceland; Greenland; and northern Europe, including the west coast of Scotland (Pickard, 1961, 1973; Syvitski and others, 1987; Cottier and others, 2010) (see figure I). Fjord systems are large transitional coastal zones, encompassing many distinct climate-hydrological-oceanographic interconnected systems that are strongly influenced by interactions with mountain ranges, freshwater input, local to hemispheric-scale atmospheric weather patterns, glacier ice fields and the open ocean (i.e. Pacific, Atlantic) (Bianchi and others, 2020; Hunt and others, 2024). These transitional coastal zones are characterized by a complex geography, including the presence of several marine habitats such as bays, estuaries, gulfs, islands, fjords and channels. Inner coastal waters are influenced by freshwater flux from rivers, which are fed from precipitation, as well as snow, glacier and sea-ice melting. The interaction of this freshwater with oceanic waters can generate strong horizontal and vertical salinity, density and nutrient gradients (see sect. 4, chap. 3). Fjords are also carbon cycle[3] hotspots where the largest amount of organic carbon[4] per unit area is buried in sediments, making them key ecosystems for carbon cycle regulation over time (Smith and others, 2015; Faust and Knies, 2019; Cui and others, 2022; Smeaton and Austin, 2022; Watts and others, 2024; Bertrand, 2025). At present, coastal fjord regions are increasingly experiencing anthropogenic impacts due to global processes (e.g. climate change) and regional activities (e.g. eutrophication) in inshore waters. Under the framework established in the third *World Ocean Assessment*, the present subchapter focuses for the first time on several fjord systems of the world (see figure I), with particular emphasis on recent studies in mainland Norway, Svalbard, Greenland, Patagonia and Pacific North America.

Figure I

Map showing the global distribution of fjord systems overlaid with map showing chlorophyll-*a* concentrations. Fjord systems of the world, with particular emphasis on recent studies in Patagonia (A), Pacific North America (B), Canadian Arctic Archipelago (C), Greenland margins (D), mainland Norway (E) and Svalbard (F)



Source: Jose L. Iriarte.

1 See www.sciencedirect.com/topics/earth-and-planetary-sciences/antarctic-region.
2 See www.sciencedirect.com/topics/earth-and-planetary-sciences/svalbard.
3 See www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-cycle.
4 See www.sciencedirect.com/topics/earth-and-planetary-sciences/organic-carbon.

2. Descriptions of the overall status

Mainland Norway

Mainland Norway has thousands of fjords along the coast (58–72°N). Fjords on the west coast are influenced by two distinct water masses: the low-salinity Norwegian Coastal Water in the upper layer and the high-salinity Atlantic Water in the lower layer beneath. The vertical structure and horizontal extent of coastal water show seasonal oscillations due to prevailing wind conditions, where alongshore northerly (southerly) winds can cause coastal upwelling (downwelling) (Sætre and others, 1988; Skarðhamar and Svendsen, 2005). Norwegian fjords are affected by land-fjord-shelf interactions such as river water input carrying organic matter and nutrients to the fjords and further to the shelf and some glaciated fjords have meltwater run-off. Some fjords have a shallow sill that prevents frequent renewal of the deep water due to the low salinity (low density) surface layer. Strong stratification and limited vertical mixing can result in long residence times of deepwater masses, which can lead to a decrease in oxygen levels and create challenging environments for local ecosystems (Aksnes and others, 2019; Darelius, 2020; Johnsen and others, 2024).

Fjords are productive due to nutrient-rich freshwater run-off from rivers and land promoting primary and secondary production. Diatom-spring blooms are most common in Norwegian fjords and as food for zooplankton. Periodically, spring blooms of the calcium carbonate forming coccolithophore have been reported in several Norwegian fjords (Kristiansen and others, 2014), observed from space (NASA; Modis). Large copepods are an important food source for fish (e.g. Atlantic coastal cod) and shrimps (Zimmermann and others, 2023). Some fjords have unique cold-water corals (Rüggeberg and others, 2011). Fixation of CO_2 by phytoplankton is a significant factor controlling the partial pressure of CO_2 (pCO_2), with the development of spring blooms in northernmost fjords. Decreased CO_2 uptake is observed in autumn due to a combined reduction of the mixed layer with the entrainment of high-CO_2 subsurface water, reduced biological production and increased surface water temperatures (Aalto and others, 2021). Time-series data reveal that the North Atlantic Oscillation significantly influences river discharge, temperature and precipitation in central Norway, making terrigenous input and erosional processes in the fjord hinterland highly sensitive to atmospheric variability. In addition, marine carbonate productivity is the primary source of calcite and calcium in all three fjords (Faust and others, 2014, 2017).

Svalbard (Spitsbergen)

Most fjords on the west coast of Svalbard exhibit a typical fjord circulation associated with a three-layer structure: a fresh surface layer in summer; a layer of intermediate water, transformed Atlantic Water in the middle to outer part; and local fjord water in the deeper part of the fjord (Hop and others, 2006; Cottier and others, 2005; Nilsen and others, 2008; Skogseth and others, 2020). The summer surface layer is mainly formed by freshwater from glacial meltwater and river run-off (Svendsen and others, 2002). East coast fjords are mostly impacted by cold Arctic water and thicker sea ice than are found in the west coast fjords. Due to the sill depth, some fjords with a shallow sill depth, such as Billefjorden, have limited inflow of water from outside the fjord to renew the bottom water, creating Arctic conditions in the inner parts (Søreide and others, 2008, 2022).

Mountains surrounding the fjords have different bedrock compositions where weathering supplies minerals and ions to the fjord (Dragańska-Deja, 2024), which impacts the marine chemistry (alkalinity) and carbonate system (ocean CO_2 uptake) (Fransson and others, 2015, 2016; Ericson and others, 2019). Glacier run-off contributes to surface stratification and nutrient supply. Sub-glacial melting affects the presence and supply of nutrients and other bio-essential substances (iron) derived from the bedrock/sediment at the bottom and transported by vertical mixing (Hopwood and others, 2020). High primary production blooms in Kongsfjorden (usually in April–June) are initiated due to shallow surface stratification and are often dominated by diatoms (e.g. Hegseth and others, 2019), and when the surface layer becomes more mixed and warmer the blooms are dominated by other species such as *Phaeocystis pouchetii* (e.g. Hoppe and others, 2024). Submarine melt in Arctic/Svalbard fjords is typically driven by the presence of warm water such as Atlantic Water and its derivative coastal water masses (Svendsen and others, 2002; Straneo and others, 2012). This melting causes low-density water to rise to the surface in the inner fjord, with positive responses on phytoplankton growth (diatoms), zooplankton (large copepods), fish, birds and sea mammals (Søreide and others, 2008; Lydersen and others, 2014; Halbach and others, 2019; Assmy and others, 2023). On the other

hand, sediments carried by glacial meltwater can affect light availability, thereby limiting primary production (Hopwood and others, 2020; Dragańska-Deja and others, 2024). Sea ice is important for ice algae (mainly diatoms) which play an important role as an early food source for many marine invertebrates such as polychaetae and roundworms (*Nematoda*) that are known to reside within sea ice (Søreide and others, 2008). Glacial surface melt is largest in summer and limited during winter, while subglacial freshwater generated all year round through geothermal and frictional heat and delayed release of subglacially stored freshwater (Vonnahme and others, 2023). Recent research in Kongsfjorden, Svalbard, reveals how freshwater run-off from marine- and land-terminating glaciers affects the biogeochemical cycles of carbon, nutrients and trace elements in the Arctic fjord system. The data show that intense carbonate weathering in proglacial catchments adds dissolved carbonates to fjord waters, mitigating the reduced buffering capacity from glacial run-off (Schmidt and others, 2025). This has also been observed in other west-Spitsbergen fjords such as Tempelfjorden (Fransson and others, 2015, 2020). Work in Smeerenburgfjorden, Kongsfjorden and Van Keulenfjorden, of western Svalbard, revealed that benthic recycling of glacially derived dissolved iron into seawater, followed by partial re-oxidation and deposition, facilitates iron transport across the fjords and potentially into adjacent shelf waters. The new data on biogeochemical processes and carbon cycling in a climate-sensitive, high-latitude fjord region aid in predictions of future Arctic ecosystem changes (Wehrmann and others, 2014).

Greenland glacial fjords

Kalaallit Nunaat (Greenland) is characterized by hundreds of glacial fjords, distributed around its perimeter, that connect the ocean with the ice sheet. Many of these fjords are associated with marine-terminating glaciers that discharge icebergs that move through the fjords and into the coastal ocean. Meltwater released into the fjords from glacier melt, iceberg melt and tundra run-off constitutes a significant freshwater export into the coastal ocean (Bamber and others, 2018). One key feature of Greenland's glacial fjords is the release of large volumes of summer surface melt at the grounding zone of marine-terminating glaciers, hundreds of metres below sea level (Moon and others, 2017; Beaird and others, 2018). The large density difference between this freshwater and the ocean water gives rise to turbulent, rising plumes, which play a key role in driving the fjord circulation, increase melting of the glacier face and upwell deep nutrients (Slater and others, 2015; Meire and others, 2017; Hopwood and others, 2018; Cape and others, 2019). Estimating the dissolved silica (dSi) flux from the Greenland Ice Sheet has been difficult, with existing estimates differing by an order of magnitude. A new study indicates a modest dissolve Si flux from run-off, with smaller contributions from melting icebergs and suspended particles (Hopwood and others, 2025). The confluence of Arctic- and Atlantic-origin waters flow alongside with the Arctic waters inshore and the Atlantic waters on the continental slope (Straneo and others, 2012). Greenland fjords are characterized by seasonal sea-ice coverage varying significantly with latitude and between east and west Greenland. Sea ice plays a vital role for Indigenous Peoples and local communities, supporting traditional livelihoods such as fishing and hunting (Krupnik and others, 2010).

Large phytoplankton blooms occur in spring as solar radiation increases and sea ice retreats (Vernet and others, 2021). The mixing of different water types and nutrient upwelling associated with glacial plumes contributes to a continued high productivity in the fjords with marine-terminating glaciers during summer (Meire and others, 2023; Juul-Pedersen and others, 2015). These high primary production blooms, often dominated by diatoms, provide a valuable food source for attracting large zooplankton communities and consequently for lower-trophic-level forage fish species such as capelin (Grønkjær and others, 2019; Laidre and others, 2008). These rich marine ecosystems are not only of ecological importance, but also of socioeconomic importance for commercial fisheries (Boje and others, 2014; Meire and others, 2017), as well as local fishing and hunting activities (Schiøtt and others, 2022; Straneo and others, 2022).

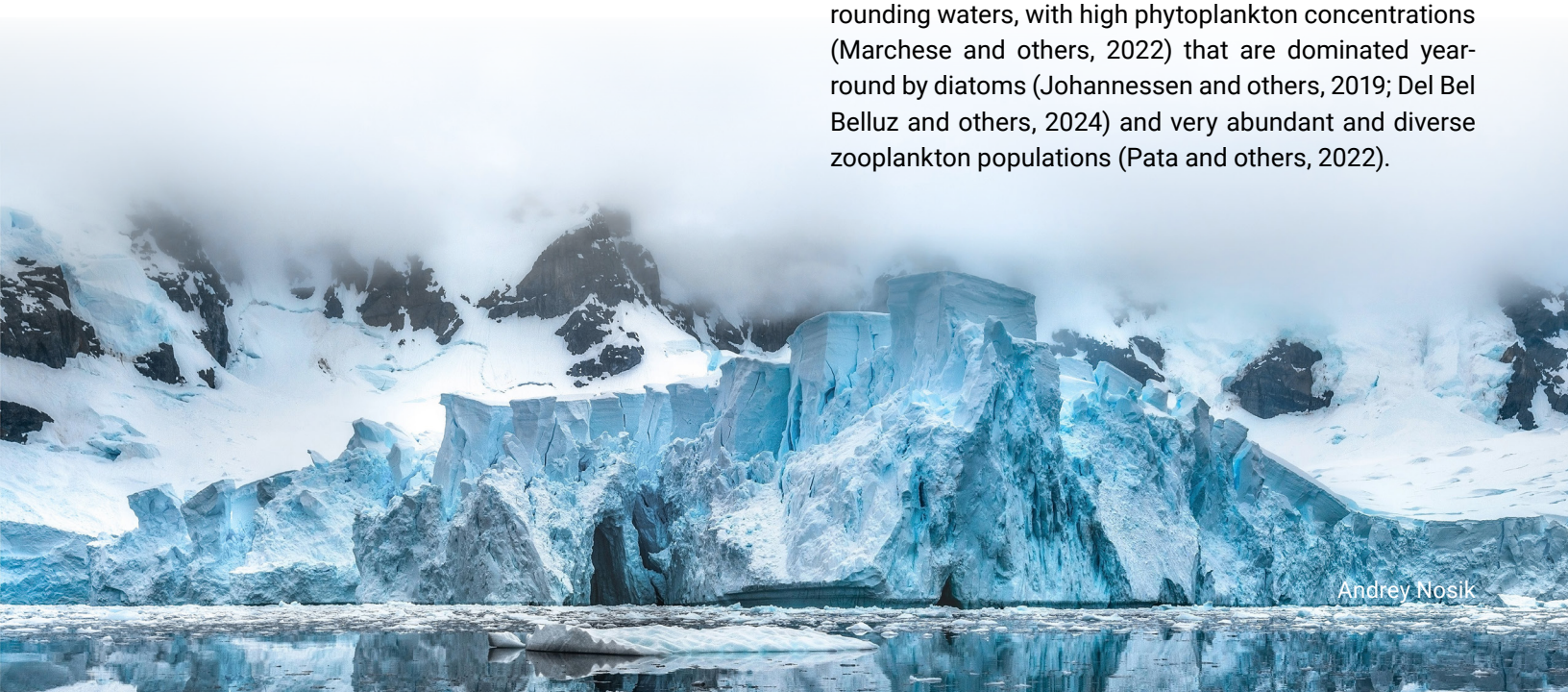
Patagonian fjords

Along the Chilean Patagonia (41–54°S), the coast is characterized by a complex geography including the presence of fjords and channels. Northern Patagonia (41–47°S) showed high freshwater input by large rivers (up to 600 $m^3 s^{-1}$) along the coast characterized by waters of low salinity and high silicic acid concentration (Jacob and others, 2014; Cuevas and others, 2019). Such discharges affect the nutrient content and their stoichiometric ratio (N:P:Si), as well as the water column structure showing a strong haline stratification (León-Muñoz and others, 2024). Their interaction with the Subantarctic Water (SAAW) generates strong horizontal and vertical salinity (and density) gradients (Saldías and

others, 2019) that contribute to maintain the phytoplankton community under high nutrient availability within the euphotic zone (Iriarte and others, 2014). The interplay between river discharges and oceanic water masses, as the principal nutrient sources, leads the maximum peak of chlorophyll-*a* to occur in the inner coastal waters during the austral spring-summer months (Iriarte and others, 2007). The pronounced salinity gradient by the riverine freshwater input can be extended to the offshore region, reaching as far as approximately 80°W, generating a strong relationship between stratification, nutrient content and surface total chlorophyll-*a* biomass (Galán and others, 2021). In contrast, southern Patagonia (47–54°S) is strongly affected by western winds (which have maximum intensity during summer) and the fluvial influence is lower compared to snow and glacial melting processes (Garreaud and others, 2009; Aguayo and others, 2024). These conditions promote a deeper mixed layer, low silicic acid and nitrate concentrations (Cuevas and others, 2019) and high content of suspended sediments, which affect the light availability in the upper layer, mainly in the inner waters (González and others, 2013; Jacob and others, 2014). The biogeochemistry of Patagonia's fjords is shaped by complex, changing factors, including fjord geomorphology, local climate, interactions of multiple water masses and atmospheric modes (Crosswell and others, 2022; Linford and others, 2024; Rebolledo and others, 2015; Sepúlveda and others, 2009). Despite this complexity, studies of water columns, surface sediments and downcore organic carbon emphasize the heterogeneity of carbon inputs and fate (González and others, 2019; Rojas and Silva, 2005; Sepúlveda and others, 2011; Silva and others, 2011).

Pacific North American fjords

In North America, fjords are located on all three ocean coasts – the Atlantic, Arctic and Pacific Oceans – but here the focus is on Pacific North American fjords, which span Washington State (United States of America), British Columbia (Canada) and Alaska (United States of America). These fjords are part of the North-East Pacific Coastal Temperate Rainforest Ecoregion, which includes prehumid and seasonal rainforests (Bidlack and others, 2021; Hunt and others, 2024). The Pacific North American fjords are fringed by mountain ranges: the Olympic range in western Washington and the coast mountain range (also known as the Cascade Range) that runs throughout Washington, British Columbia and Alaska. Freshwater flows from the coastal mountains to the coast via thousands of small coastal rivers and five large continental rivers (Giesbrecht and others, 2021). Rivers are observed at the heads of most fjords and the seasonality of the river depends on whether the source of the freshwater is rain, snow or glacial melt (Morrison and others, 2011). In British Columbia, there are 42 fjords that are longer than 18.5 km and of these, the outer sill depth ranges from 6 to 490 m, the maximum depth ranges from 75 to 730 m, and the length ranges from 33 to 130 km (Pickard, 1961). In most cases there are three water types in fjords: deep water (greater than sill depth), which in most fjords is seasonally modified by deepwater renewal (Farmer and Freeland, 1983); intermediate water (above sill and below surface water), which can be modified by wind-driven or advective processes (Jackson and others, 2022); and surface water, which is driven by estuarine circulation (Pickard, 1961). In recent research it has been pointed out that the ecosystem within fjords is different from surrounding waters, with high phytoplankton concentrations (Marchese and others, 2022) that are dominated year-round by diatoms (Johannessen and others, 2019; Del Bel Belluz and others, 2024) and very abundant and diverse zooplankton populations (Pata and others, 2022).


Andrey Nosik

3. Region-specific changes

Mainland Norway

Freshwater input is increasing to the coastal zone which is an important area for fisheries (cod, salmon, shrimp) and aquaculture. Cod egg dispersion models show negative impacts of increased low-density water with low oxygen (Stenevik and others, 2008). There is recent evidence that coastal waters in mainland Norway are becoming lighter due to climate change, resulting in a stronger stratification in the fjord basins with reduced mixing and consequent deoxygenation in fjords (Johnsen and others, 2024). An estimated increase of 0.6°C in temperature in the fjord basins after 1990 showed that basin water renewal occurred less frequently in most fjord basins along the Norwegian coast (Johnsen and others, 2024). Masfjorden, in southern Norway, is one of the fjords showing recent oxygen-depleted basin water (Pitcher and others, 2021). Impacts of ocean acidification include: some glaciated fjords have meltwater run-off that dilutes buffering ions (and alkalinity), increases CO_2 uptake and increases ocean acidification (Aalto and others, 2021; Jones and others, 2020). Human activities – such as shipping, aquaculture (see subsect. 5A, subchap. 1D), fishing and pollution (e.g. mining waste; see sect. 4, chap. 6), and climate stressors such as ocean warming and acidification – negatively impact the fjords. Because of the unique and diverse environment, several such fjords (i.e. Ytre Hardangerfjorden fjord) have recently become marine protected areas (MPAs).

Svalbard

Ocean warming of 0.7°C per year in winter and 0.6°C per year in summer is observed on the shelf of western Spitsbergen and Isfjorden (Skogseth and others, 2020) and a decline in sea ice is reported in Kongsfjorden (Pavlova and others, 2019; Gerland and others, 2020). Glaciers in Svalbard are melting and retreating and freshwater input to the coastal zone is increasing (Kohler and others, 2007; Geyman and others, 2022) due to warming (e.g. Foss and others, 2024). Fjords in Svalbard experience increased ocean acidification due to increased glacial discharge and meltwater-induced CO_2 uptake (e.g. Fransson and others, 2016; Cantoni and others, 2020). These waters are further modified by accumulated dissolved inorganic carbon from sea-ice brine rejection and respiration of organic matter which further contributes to acidification (Ericson and others, 2019; Fransson and others, 2015, 2016). Studies in Kongsfjorden (west Spitsbergen) showed inter-annual variability in biogeochemical properties with lower aragonite saturation (Ω_{ar}) and pH (indicators of ocean acidification) in cold years with extensive sea-ice cover, relative to warm years with a greater influence from warm and saline Atlantic Water inflow (Fransson and others, 2016). Differences in phytoplankton spring bloom composition in Kongsfjorden were observed in contrasting years where in a cold year with more sea ice the spring bloom was dominated by diatoms, and in a warm year, with less sea ice, the spring bloom was dominated by haptophyte (Søreide and others, 2010; Assmy and others, 2023). In years with less surface stratification, warmer water and deeper mixed layer, the blooms were dominated by species such as *Phaeocystis pouchetii* (Hoppe and others, 2024). Moreover, the reported decreased sea-ice presence in Svalbard fjords (Pavlova and others, 2019) will lead to less ice algae and earlier phytoplankton blooms (Søreide and others, 2008), resulting in changes in the diversity of sea-ice protist (e.g. diatoms) and ice-associated fauna (Hop and others, 2020). In sediments of Kongsfjorden in Svalbard, benthic remineralization could increase nutrient sources like iron (Fe). Inter-annual variations in primary productivity, expected to intensify with global warming and changes in glacial sediment delivery, will affect benthic iron and sulfur cycling. Over time, this may lead to decreased benthic Fe fluxes. With glacial retreat and shifts in productivity, fjords like Kongsfjorden may become less efficient carbon sinks, burying less organic matter in deep sediments (Herbert and others, 2022). Seepage of methane is reported in most Svalbard fjords and natural gas below the permafrost, with methane flares measured in Isfjorden, Kongsfjorden and Van-Mijenfjorden (Hodson and others, 2025). With warming, permafrost thawing and methane release into the fjords will likely increase with impacts on carbon cycling in the fjords and shelves. Knowledge gaps on the methane dynamics in Svalbard still exist (Hodson and others, 2025).

Greenland's margins

Climate change, including the rapid warming of the Arctic, is resulting in significant changes over Greenland and along its coastal margins. These changes include the retreat of glaciers, increased surface melt (Mankoff and others, 2020, 2021), reduced sea ice (Cooley and others, 2020) and warming air temperatures (Box and others, 2009). These trends are superimposed with long-term modes of variability, such as the Arctic and North Atlantic Oscillations and the Atlantic Multidecadal Oscillation, which account for a significant fraction of the variability

in this region (Hanna and others, 2021). Records of physical and chemical properties and of ecosystem and fisheries variability in the fjords and in the coastal region are, however, scarce – making it challenging to quantify change that has already occurred. Proxy records derived from fjord sediment archives offer valuable insights into past changes beyond the instrumental era (Heikkilä and others, 2022). Fjord sediments simultaneously record changes in sea ice, ice-sheet discharge, ice-ocean interactions and associated ecosystem responses (Ribeiro and others, 2017; Vermassen and others, 2019). Proxy-data studies from Greenland fjords from both West and East Greenland have revealed multidecadal changes in the inflow of Atlantic-derived warm water and its relationship with glacier dynamics (Andresen and others, 2012; Vermassen and others, 2019). They also have revealed that present-day impacts of freshwater discharge on fjord productivity are unprecedented in centuries to millennia (Oksman and others, 2022, 2024). The increase in the upwelling of nutrients associated with subglacial discharge may be partly offset by the retreat of glaciers into shallower water – thus reducing the ability to upwell deep nutrients (Meire and others, 2017; Hopwood and others, 2020). Sea-ice decrease is impacting wintertime travel and fishing, on which Indigenous Peoples and local communities rely for sustenance, and threatens the future viability of key polynya ecosystems (Ribeiro and others, 2021). Sea-ice cover serves as winter refuges for marine mammal species that are harvested by Indigenous People in Greenland's fjords (Heide-Jørgensen and others, 2013). At the same time, reduced sea-ice resulted in increased primary productivity as light limitations are reduced and wind-induced mixing increased (e.g. Baffin Bay and the Arctic Ocean) (York and others, 2020; Frey and others, 2020).

Patagonia

The Patagonia region is undergoing an increasing anthropogenic affectation due to global phenomena, including hydrological anomalies, glacier retreat, climatological shifts (Aguayo and others, 2019, 2024; Garreaud and others, 2009) and regional productive activities such as large-scale aquaculture farms (salmon and mussels) allocated along inshore waters (Navedo and Vargas-Chacoff, 2021). In northern Patagonia (41–44°S), climate change projections forecast 20% less rainfall in the next decade (Aguayo and others, 2019), which will negatively affect the annual dynamics of large river streamflows, water chemistry (silicic acid) and pelagic (mollusc larvae) and benthic organisms inhabiting fjord systems (van Leeuwen and others, 2021), as well as the physical support (weakening of haline stratification and increase of sea-surface temperature; León-Muñoz and others, 2024). Recurrent harmful microorganisms' events observed in coastal and oceanic regions off northern Patagonia since 2016 coincided with the synergy of remote climatic phenomena (El Niño) and global warming that led to very dry conditions, higher-than-normal solar radiation, high sea-surface temperatures, and reduced wind velocities (León-Muñoz and others, 2018). Significant mass loss (65%) in the Patagonia icefields (47–55°S) may continue in the future (Minowa and others, 2022; Aguayo and others, 2024), where ocean-terminating and land-terminating fjords are likely exposed to increasing freshwater run-off (freshening effect) and increasing rain precipitation (Garreaud and others, 2013). Patagonian fjords and inner seas are affected by human-induced global changes, including climate-ocean events, altered freshwater inputs, harmful algal blooms, settlement, aquaculture, glacial melt and coastal hypoxia (González and others, 2019; Iriarte, 2018; Linford and others, 2024; Quiñones and others, 2019).

Pacific North America

Data of temperature, salinity and oxygen have been collected since 1951 in British Columbia fjords. Recent work found that deep water warmed by 1.2°C to 1.4°C and lost 0.4 to 0.7 mL L^{-1} of oxygen from 1951 to 2020 (Jackson and others, 2021). These changes are explained by the upwelling of offshore water that was warmed by the 2014–2016 marine heatwave to fjords via deepwater renewal (Jackson and others, 2018; Alin and others, 2024); the 2014–2016 marine heatwave water lingered in deep fjord water until 2020 (Jackson and others, 2021). Waters in fjords are often acidic (Hare and others, 2020) and impacted by random events (Alin and others, 2024).

Glaciers in British Columbia are melting rapidly, and it is predicted that the volume of glacial ice will shrink by approximately 70% by 2100 relative to 2005 (Clarke and others, 2015). In addition to altering the amount of freshwater transported to the ocean, as the glaciers melt, they cause extreme events such as the 2020 outburst flood that destroyed salmon habitat and advected tons of inorganic and organic sediments into Bute Inlet (Geertsma and others, 2022). There is evidence that these changes to the seasonality and amount of freshwater that enters fjords are impacting the timing of the spring bloom (Wolfe and others, 2015; Hunt and others, 2024; Del Bel Belluz and others, 2024), as well as zooplankton dynamics (Tommasi and others, 2013).

4. Outlook

General awareness of fjords and the key ecosystem services offered by them are essential to determine actions on management under natural disturbances as well as present and projected climate change scenarios. Linking physical-ecological and socioeconomic structures and their ecosystems functions is key to proposing and incorporating both mitigation and adaptation processes such as nature-based solutions and climate refugees. Long-term monitoring approaches designed and coordinated by scientists and stakeholders must be undertaken in existing and future marine and terrestrial protected areas located in fjord systems. In the present subchapter and others, such as cold-water corals and sponges (CWCS) (sect. 4, subchap. 5E), estuaries and deltas (sect. 4, subchap. 5F) and small-scale aquaculture (subsect. 5A, subchap. 1D), it has been pointed out that fjord regions are under threat from intensive human activities (including land-use, aquaculture, dams and tourism) and the effects of climate change (including warming, freshening, ice loss, permafrost thawing, erosion and sea-level rise).

5. Key remaining knowledge and capacity changes and any new gaps

- A critical knowledge gap exists for fjord habitats, as only a small percentage of the world's fjords have been studied.
- A change from marine-terminating glaciers to land-terminating glaciers would determine changes in surface and sub-glacial melt, sediment supply that limits light, stronger stratification and nutrient limitation for primary production, changes in species composition and, ultimately, the dynamic of carbon flux.
- The contribution to the global carbon cycle of methane emissions from melting ice sheets and glaciers in the Arctic is unknown.
- The resilience of fjord systems to hydrologic changes (precipitation, melting, run-off) and oceanographic changes (water masses, stratification, nutrient stoichiometry) to present conditions remains a major gap.
- Advances in modelling research, such as in relation to the impacts of freshening, coastal acidification, sea-surface warming, and deoxygenation processes are lacking and need to be compared with in situ studies approaches.

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Chapter 6
Pressures



Fan Ping

Subchapter 6A
Invasive species

Key points

- Globally, the spread of non-indigenous species (NIS) continues, exacerbated by climate change and human activities, negatively affecting some of the most vulnerable marine ecosystems.
- The introduction of NIS continues to negatively impact native species and habitats, affecting global ecological, socioeconomic, cultural and human health outcomes.
- Despite the crucial importance of preventing the introduction of NIS, few mandatory regulations or policies exist globally or regionally.
- A significant gap remains in systematic monitoring and information-sharing about NIS at multiple temporal and spatial scales, which undermines management and response efforts.
- A lack of long-term studies on NIS impacts hinders risk identification and reduces the effectiveness of post-invasion management efforts.

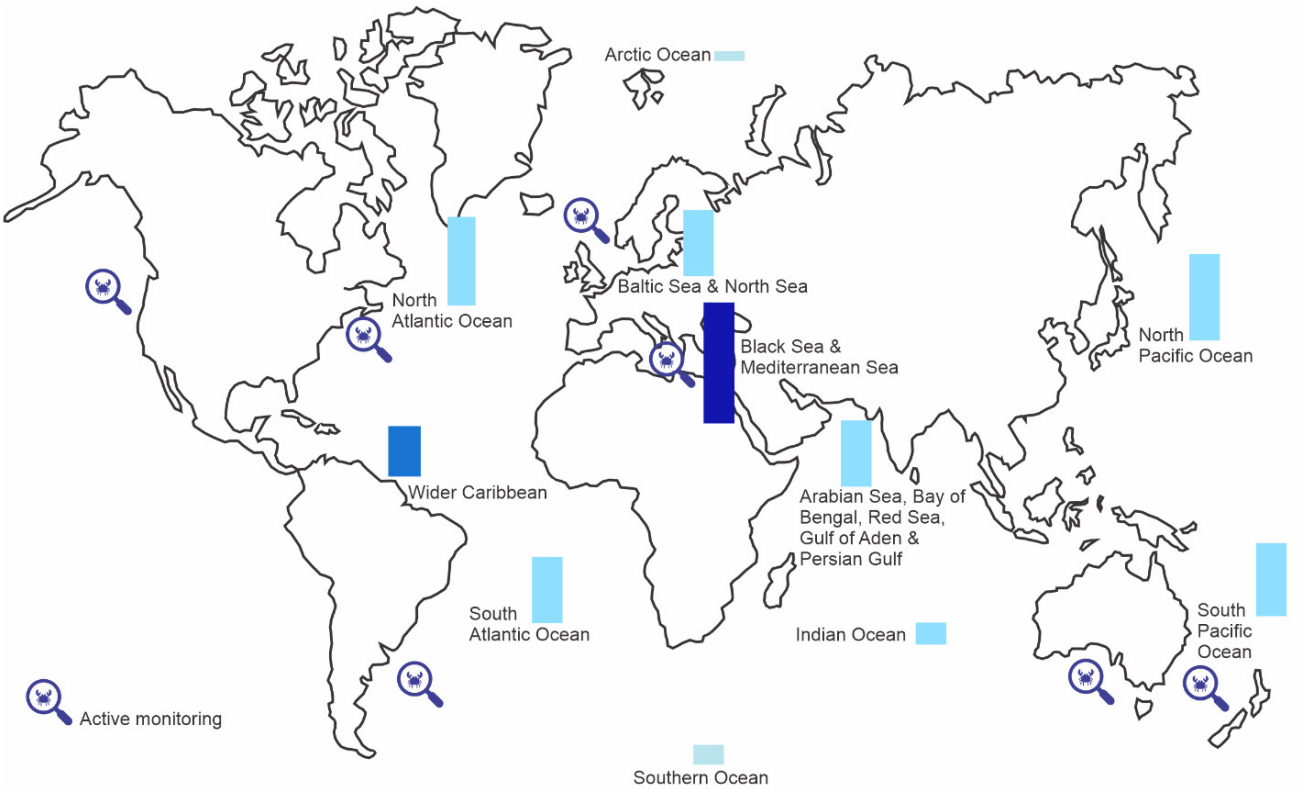
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1. Introduction

NIS have been detected in ecosystems worldwide, but the type of species, their diversity and population sizes are affected by biotic and abiotic factors (see figure I). The ongoing accidental or intentional introduction of species significantly affects marine ecosystems, resulting in biotic homogenization and threatening biodiversity, ecosystem services, human health and socioeconomic outcomes (Schwindt and others, 2022; Ojaveer and others, 2023; Roy and others, 2024; Simberloff and others, 2024; Zaiko and others, 2024). Any species may become invasive under favourable conditions (Williamson, 1999; United Nations Environment Programme (UNEP), 2002). The approach adopted in the present subchapter is therefore a precautionary one, under which all NIS are considered while acknowledging that some native species can also become invasive, such as crown-of-thorns starfish (*Acanthaster planci*) (Hoey and others, 2016; Guareschi and others, 2024).

Information on NIS varies, with strong biases in the breadth and depth of taxonomic coverage and expertise towards larger, more conspicuous species and those with economic consequences (Watkins and others, 2021; Schwindt and others, 2022). As noted in the second *World Ocean Assessment*, there is a lack of, and continuing need for, large-scale systematic surveys on NIS. In addition, the context-dependent nature of many NIS makes it difficult to generalize (Carlton and Schwindt, 2024; see figure II and table). Although determining which NIS to prioritize for management is challenging, there are an increasing number of screening and risk assessment tools to support decision-making (Dahlstrom and others, 2011; Kumschick and Richardson, 2013; Srėbalienė and others, 2019; Wilcox and others, 2024).

Figure I
Marine non-indigenous species across the various ocean basins

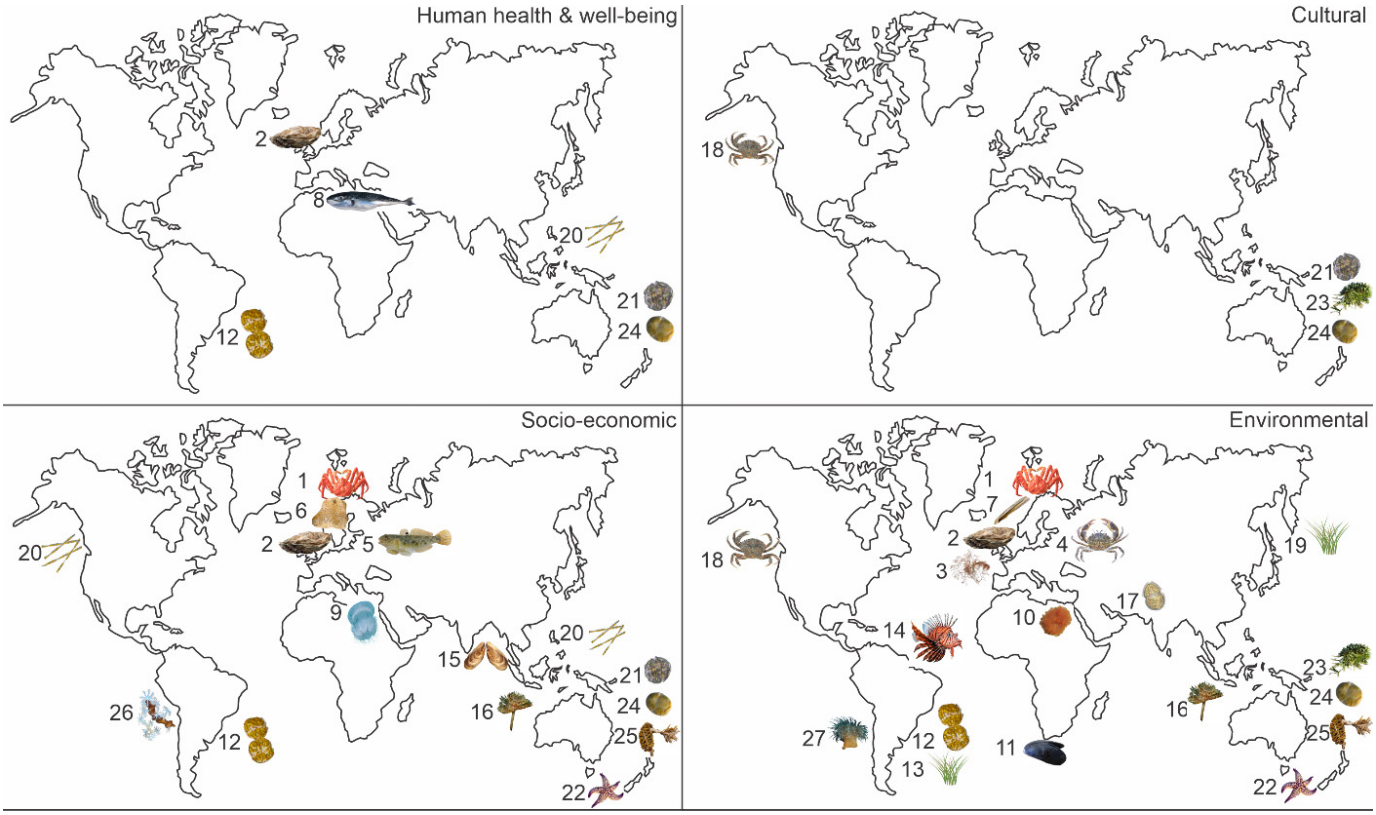


Source: Prepared by the writing team.

Note: The height of the bars reflects the relative abundance of documented alien taxa, while darker colours indicate a greater increase since the publication of the second *World Ocean Assessment*. Regions that have active monitoring programmes are indicated.

Figure II

Species that have affected human health and well-being, socioeconomic and cultural assets and the marine environment



Source: Prepared by the writing team.

In global policy documents, NIS are clearly identified as a major threat to biodiversity. The targets set out in the Kunming-Montreal Global Biodiversity Framework, developed under the Convention on Biological Diversity, directly address NIS. In particular, target 6 requires States to minimize the impacts of NIS on biodiversity and ecosystem services through preventative measures aimed at reducing the rates of introduction and establishment of NIS by at least 50% by 2030. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has recognized the negative impacts of invasive species around the world (IPBES, 2023). Several important considerations have been highlighted in IPBES assessments, including local extinctions caused by marine species such as *Pterois volitans, Caulerpa taxifolia* and *Mytilus galloprovincialis* (Bacher and others, 2023; Schwindt and others, 2024). Given that marine protected areas (MPAs) are one internationally accepted tool to conserve biodiversity, it is surprising that efforts to characterize NIS in MPAs and to better understand their potential impacts have been limited (Soares, 2018; Mendez and Schwindt, 2024). Meanwhile, vectors such as recreational vessels are creating invasion networks by linking MPAs to invasion hotspots (Iacarella and others, 2020), thus compromising conservation objectives.

As a global ecosystem stressor, NIS can belong to any taxa (see Briski and others, 2024; also sect. 4, chaps. 4 and 5). Some marine plants have been introduced globally, including habitat-altering species belonging to the genera *Spartina* and *Phragmites* (see subchap. 4H). Bivalves, such as the Pacific oyster (*Magallana gigas*), have been introduced globally for aquaculture purposes, but often with negative consequences for native biodiversity (Bacher and others, 2023; Di Blasio and others, 2023). White spot syndrome, a viral disease that affects most commercially cultivated marine shrimp species globally (Flegel, 1997; Lotz, 1997), has spread to most shrimp culture countries (Yan and others, 2007). NIS have been shown to benefit from habitats that were already stressed or degraded by other human impacts (see subchaps. 6B–6E). In addition, many NIS have socioeconomic or cultural impacts (Campbell and Hewitt, 2018; Bortolus and Schwindt, 2022; see also sect. 5).

Table

Non-indigenous species that have had demonstrable impacts in ocean basins

#	Species	Type of impact	Description	References
Arctic				
1	Red king crab *Paralithodes camtschaticus*	Socioeconomic; environmental	Despite being fished commercially in some areas, causes losses to fisheries in other areas; reduces biodiversity	Sundet and Hoel, 2016; Falk-Petersen and others, 2011
North Atlantic Ocean				
2	Pacific oyster *Magallana gigas* (previously known as *Crassostrea gigas*)	Human health and well-being; socioeconomic; environmental	Carries disease-causing viruses; is extensively farmed; alters habitat structure, phytoplankton communities and food webs; reduces biodiversity	Ueki and others, 2021; Des and others, 2022; Troost, 2010
3	Red seaweed *Dasysiphonia japonica*	Environmental	Reduces seaweed diversity	Newton and others, 2013
Baltic Sea				
4	Mud crab *Rhithropanopeus harrisii*	Environmental	Has caused a regime shift through consumption of native species	Kotta and others, 2018
5	Round goby *Neogobius melanostomus*	Socioeconomic	Negatively affects commercial species, but is also fished commercially	Ustups and others, 2016
North Sea				
6	Carpet sea squirt *Didemnum vexillum*	Socioeconomic	Threatens shellfish aquaculture	Gittenberger, 2010
7	Atlantic jackknife clam *Ensis directus*	Environmental	Alters food webs as it becomes a dominant food source	Tulp and others, 2010
Mediterranean Sea				
8	Silver-cheeked toadfish *Lagocephalus sceleratus*	Human health and well-being	Causes poisoning and human fatalities	Ulman and others, 2024
9	Nomad jellyfish *Rhopilema nomadica*	Socioeconomic	Negatively affects commercial fisheries	Ghermandi and others, 2015
10	Epiphytic algae *Lophocladia lallemandii*	Environmental	Smothers native seagrasses	El Zrelli and others, 2021
South Atlantic Ocean				
11	Mediterranean mussel *Mytilus galloprovincialis*	Environmental	Changes rocky shore communities and outcompetes native mussels	Sadchatheeswaran and others, 2015
12	Dinoflagellate *Alexandrium* sp.	Human health and well-being; socioeconomic; environmental	Causes poisoning when consumed, resulting in losses for artisanal fisheries; has even caused the death of whales	Gayoso and Fulco, 2006
13	Smooth cordgrass *Spartina alterniflora*	Environmental	Alters ecosystem functioning	Bortolus and others, 2015

Table (*continued*)

#	Species	Type of impact	Description	References
Wider Caribbean				
14	Lionfish *Pterois* spp.	Environmental	Consumes native fish	Côté and others, 2013
Indian Ocean				
15	Black-striped mussel *Mytilopsis sallei*	Socioeconomic	Clogs water intakes, fouls ships and maritime infrastructure	Rao and others, 1989; Tan and Morton, 2006
16	Mediterranean fanworm *Sabella spallanzanii*	Socioeconomic; environmental	Fouls mussel farms; alters recruitment of native sessile communities	Hewitt, 2003; Halloway and Keough, 2002
Persian Gulf				
17	Dinoflagellate *Heterocapsa circularisquama*	Environmental	Has caused mass mortality of bivalves	Saburova and others, 2022
North Pacific				
18	European green crab *Carcinus maenas*	Environmental; cultural	Eats native species, competes with native crabs and degrades eelgrass habitats	Howard and others, 2019; Barclay and others, 2024; Fisher and others, 2024
19	Smooth cordgrass *Spartina alterniflora*	Environmental	Alters physical, biological and biochemical processes	Lee and others, 2024
20	Diatoms of the genus *Pseudo-nitzschia*	Human health and well-being; socioeconomic	Their blooms cause poisoning and fishery closures	Kim and others, 2018; Perry and others, 2023
South Pacific				
21	Dinoflagellate *Alexandrium catenella*	Human health and well-being; socioeconomic; cultural	Causes shellfish poisoning, which forces commercial and recreational fisheries to close	Trainer and others, 2020
22	Northern Pacific seastar *Asterias amurensis*	Socioeconomic; environmental	Predates upon native and commercially important species	Ross and others, 2002, 2003
23	Green algae *Caulerpa* spp.	Cultural; environmental	Overgrows benthic habitats and smothers culturally important seagrass	Scott, 2022; Gribben and others, 2013
24	Dinoflagellate *Karenia mikimotoi*	Human health and well-being; socioeconomic; cultural; environmental	Causes poisoning and skin irritation in people; kills native species; prevents collection of marine resources by communities and negatively affects fisheries	Li and others, 2019
25	Wakame *Undaria pinnatifida*	Socioeconomic; environmental	Fouls aquaculture infrastructure and outcompetes native kelp	Carnell and Keough, 2014; Watts and others, 2015
26	Snowflake coral *Carijoa riisei*	Environmental	Displaces native corals	Sanchez and Ballesteros, 2014
27	Plumose anemone *Metridium senile*	Socioeconomic	Overgrows aquaculture infrastructure	Häussermann and others, 2022

Source: Prepared by the writing team.

2. Changes since the second *World Ocean Assessment*

Globally, significant gaps remain in the detection and reporting of, and response to, NIS, thereby limiting the understanding of the associated ecological, economic and cultural impacts, which in turn limits the ability to predict the impacts of NIS in new locations (Schwindt and others, 2022). The continued introduction and spread of NIS compromise the achievement of up to 11 of the 17 Sustainable Development Goals and other global conservation efforts. Although vectors and pathways have only been partially characterized globally, commercial shipping, the Suez Canal and other artificial waterways, aquaculture, recreational boats and aquarium releases are responsible for the introduction and spread of most NIS (Bailey and others, 2020; Seebens and others, 2021; Menezes and others, 2022; Guerra-García and others, 2023; Aylagas and others, 2024). Marine debris and litter is an emerging vector globally (Therriault and others, 2018; Audrézet and others, 2021; Galil, 2023), and unprecedented pathways between Antarctica and other continents have been observed (Dawson and others, 2024).

Biogeographical barriers can limit the natural spread of NIS, depending on their permeability; the strength and location of such barriers, however, are being affected by climate change (Krumhansl and others, 2023). Climate change also results in more frequent and intense marine heatwaves, which facilitates the spread and impacts of NIS. In the Mediterranean region, New Zealand and temperate regions of Australia, the nearshore ecosystem has proved to be highly vulnerable to recurrent heat-induced mass mortality events over the past four decades (Thomsen and others, 2019; Verdura and others, 2019; Tait and others, 2021; Wernberg, 2021; Bell and others, 2023). That scenario is likely to be repeated in multiple ocean basins. While most research has documented NIS impacts on ecological and, to a lesser extent, socioeconomic endpoints, there is growing recognition of cultural impacts of NIS in some ocean basins. An exhaustive analysis of NIS impacts is beyond the scope of the present subchapter, but figure II and table show examples of the types of impacts that certain NIS can have.

3. Region-specific changes

Arctic Ocean

There continue to be significant knowledge gaps for the Arctic Ocean, with no new reports since the publication of the second *World Ocean Assessment*. Some studies have shown, however, that NIS from polar and subpolar environments could establish in the Arctic Ocean, especially under multiple climate change scenarios and projections of increased vessel traffic (Goldsmit and others, 2020). For example, the red king crab (*Paralithodes camtschaticus*) originally introduced to the Barents Sea to establish a fishery has now spread to Norway, causing significant ecological and economic impacts (Sundet and Hoel, 2016).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

By July 2023, 1,671 NIS and cryptogenic marine and oligohaline species had been reported in European seas (Katsanevakis and others, 2023), and that figure is likely a significant undercount. By December 2020, 1,006 NIS (excluding cryptogenic and data-deficient species) had been reported in Mediterranean waters alone, half of which were Erythraean species introduced through the Suez Canal (Galanidi and others, 2023), which suggests that such invasions will continue. The number of NIS in the Black Sea is unclear, but recent accounts have identified 81, in addition to 113 cryptogenic, cryptogenic-expanding and data-deficient species (Öztürk, 2021; Băncilă and others, 2022; Shalovenkov, 2022). The number of NIS newly introduced into the Baltic Sea was higher during the most recent Baltic Marine Environment Protection Commission (HELCOM) assessment period (13 NIS in the period 2016–2021, compared with 12 in the period 2011–2016; HELCOM, 2023). Meanwhile, the number of NIS newly introduced each year into the Greater North Sea has varied from three to five over the period 2018–2021, in a reversal of the long-term increasing trend (International Council for the Exploration of the Sea (ICES), 2022). The rate of introduction of new NIS has decreased in regions II (Greater North Sea), III (Celtic Seas) and IV (Bay of Biscay and Iberian Coast) of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission) (Stæhr and others, 2022).

South Atlantic Ocean and wider Caribbean

National scale reassessments have not been conducted since the publication of the second *World Ocean*

Assessment, but high-profile species such as the sun coral (*Tubastraea* spp.) continue to spread (Dutra and others, 2023). At least 10 NIS that had been reported previously in the South-West Atlantic are now widely distributed, the ranges of another 24 are expanding (Schwindt and others, 2020; Teixeira and Creed, 2020), and several others are expected to spread (Schwindt and others, 2022; Soares and others, 2022). In Argentina and Uruguay, six NIS hotspots have been identified, mostly associated with ports and cities (Reyna and others, 2023).

In the South-East Atlantic, almost 100 NIS have been detected from South African coastlines (Robinson and others, 2020). Although there are efforts to establish routine monitoring programmes (Loureiro and others, 2021), detections of new incursions remain largely coincidental. In South Africa, the failure of the first attempt to eradicate the European green crab (*Carcinus maenas*) has reinforced the need for preventative management (Mabin and others, 2020).

In the wider Caribbean, one recent assessment reported 33 NIS (Alidoost Salimi and others, 2021), which is likely an underestimate. In this vast region, lionfish (*Pterois* spp.) are probably the most widespread and studied NIS, with ecological, economic and human health impacts (Côté and others, 2013).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

The Red Sea is a major shipping route, making it vulnerable to the introduction of NIS. The status of NIS in the region is uncertain, however, due to a lack of monitoring efforts and baseline biodiversity information. Clarke and others (2020) identified 35 NIS in the Persian Gulf and the Gulf of Oman, and additional efforts are required to confirm the invasive status of other species. Fernández and others (2022) conducted an environmental DNA study in the Gulf of Aqaba and found that more than 36% of exact sequence variants detected were non-native. Aylagas and others (2024) and Shchepanik (2022), using molecular methods, identified 16 NIS newly introduced into the Red Sea, including Ascidians, Bryozoans and Crustaceans, as well as the barramundi (*Lates calcarifer*), a species introduced for aquaculture.

North Pacific Ocean

Although large-scale studies of NIS in the North Pacific have not been updated, several of the 747 reported in the second *World Ocean Assessment* continue to spread within the basin, and the increasing trend in invasions continues (Bailey and others, 2020). Lyons and others (2020), using habitat suitability modelling, identified the southern Salish Sea as an invasion hotspot, along with parts of the outer coasts of Washington and Oregon, and found that existing hotspots were predicted to shift or expand and new ones were likely to appear in a future climate scenario. Species such as the European green crab (*Carcinus maenas*) continue to spread towards the North Pole along the west coast of North America, with significant impacts on eelgrass (Howard and others, 2019) and other native species (Grosholz and others, 2000). In China, the introduction of *Spartina* to prevent coastal erosion resulted in extensive spread, with dense stands drastically altering the nearshore environment (Chung, 2006; Zhang and others, 2017). China implemented a diverse series of policies, regulations and ecological restoration projects that have effectively controlled the spread of *Spartina alterniflora* (Li and others, 2022; Luo and Ma, 2025). By October 2023, this annual effort had cleared approximately 300 km^2 (Dong and others, 2024).

South Pacific Ocean

Large-scale surveys and surveillance continue to be conducted in Australia and New Zealand, with increasing baseline evaluations elsewhere in the South Pacific. There are also continued efforts to develop tools to aid vector management and surveillance in the South Pacific (Secretariat for the Pacific Regional Environment Programme (SPREP), 2022). Nevertheless, NIS continue to spread (Lane and others, 2022). Some declared pests, including *Undaria, Asterias* and *Sabella*, are being managed in Australia, but early detection and rapid response tools generally are lacking. The recent arrival and rapid spread of two habitat-forming subtropical algae in New Zealand, *Caulerpa brachypus* and *Caulerpa parvifolia*, caused national concern about impacts on native habitats, recreational and commercial fisheries and the spiritual and cultural resources of the Māori, the Indigenous People of New Zealand (Evans, 2022). NIS impact studies have included an examination of the likelihood of ecosystem impacts due to key invaders (Soliman and Inglis, 2018; Atalah and others, 2019; Tait and others, 2020, 2023a), and the impacts on social and cultural values (Campbell and Hewitt, 2018; Manaaki te Awanui and National Institute of Water and Atmospheric Research (NIWA), 2021; Campbell and others, 2024).

Southern Ocean

There are also significant knowledge gaps with respect to NIS in the Southern Ocean. A horizon scanning exercise identified the risk of introduction of invertebrate species into the Antarctic Peninsula owing to ballast water and hull fouling (Hughes and others, 2020). Unless appropriate biosecurity measures are implemented, the rate of invasions in this region is likely to increase (McCarthy and others, 2022).

4. Key remaining knowledge and capacity gaps and new gaps

Critical data gaps and a lack of standardization and of frameworks for facilitating comparisons make large-scale assessments such as the *World Ocean Assessment* challenging (Carlton and Schwindt, 2024). Efforts need to be made to ensure that NIS records are freely accessible to the global community by removing access and language barriers. Knowledge brokers could fulfil the role of bridging such gaps by connecting data holders to managers.

NIS are a major threat to biodiversity. Nevertheless, distinctions are not made between native and non-native species in most biodiversity studies, and such studies are incomplete for most of the world's oceans. While some global registers, including the World Register of Marine Species (WoRMS) and the Ocean Biodiversity Information System, are attempting to track NIS separately, significant gaps remain. New molecular methods are improving the understanding of biodiversity in general (Adams and others, 2023) and of NIS broadly (Zhan and others, 2014; Westfall and others, 2020; Lavrador and others, 2024), but a lack of verified DNA barcodes and standard protocols for using them for surveillance has only confounded the problem (Couton and others, 2022; Zaiko and others, 2022; Bowers and others, 2021). In this context, and as the homogenization of the world's oceans accelerates, it will be increasingly difficult to ensure that NIS are correctly identified.

Prevention is key to limiting the impacts of NIS, but prevention strategies are limited. Efforts to prioritize continuous monitoring and early detection are also needed. Global efforts have been undertaken to reduce the risk of introduction of NIS under the International Convention for the Control and Management of Ships' Ballast Water and Sediments (Ballast Water Management Convention) and biofouling management guidelines, while regional efforts have included the application of the ICES Code of Practice to reduce risk of introduction of NIS from aquaculture activities. Nevertheless, many vectors and pathways remain unregulated, and the effectiveness of those regulations that do exist is uncertain (Outinen and others, 2024). There are also regional efforts to reduce the risk to the North-East Atlantic and the Baltic Sea through the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention), in addition to several national efforts (Castro and others, 2018). However, this fragmented and patchwork research and policy environment, which differs across regions and countries, only hinders the ability to identify and respond to NIS risks. One holistic, interdisciplinary approach that has been proposed is the "One Biosecurity" model (Hulme, 2020, 2021; Hulme and others, 2023; Bray and others, 2024), which is aimed at reducing risks across ecosystem components by reducing redundancy and increasing collaboration. Such an approach, if applied broadly, would help managers to identify NIS that need to be prioritized for early detection, control or management, all of which require context-specific approaches to ensure the effectiveness of the measures implemented.

In most global ocean basins, the bulk of the attention and research effort is focused on a few high-risk or high-profile NIS (Watkins and others, 2021; Ojaveer and others, 2023), which limits the comprehensive identification of NIS impacts across a number of categories, including socioeconomic and cultural impacts, and the understanding of how NIS are being redistributed by human activities. This ultimately compromises the ability to determine the achievement of the Sustainable Development Goals. In addition, most studies have been conducted in coastal waters, with limited attention paid to the deep sea, areas beyond national jurisdiction and polar regions. Baseline information for such areas, which are logistically much more difficult to access, is virtually non-existent despite the known presence of NIS and an increase in human activities. NIS are implicated in all marine-based industries (e.g. fishing, aquaculture, transport, energy and mining), and those industries are growing faster than other global industries, which compromises the achievement of a sustainable blue economy. Thus, prevention and mitigation must be increasingly considered as these industries develop to ensure the negative consequences of NIS are fully addressed (Carvalho and others, 2023; Aylagas and others, 2024).

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Subchapter 6B
Erosion and sedimentation

Key points

- Global and regional coastal erosion and sedimentation assessments based on satellite data have proliferated since the mid-2010s, offering insights into trends and patterns of change. However, uncertainties and limitations of satellite-derived methods must be carefully considered.
- People, property and economic activities are increasingly exposed to coastal flooding and erosion across all latitudes, which is often associated with climate change impacts.
- The literature has been focused more on coastal erosion than on sedimentation changes.
- Growing evidence suggests that coastal erosion in the Arctic is intensifying due to permafrost thaw and increased wave action. This accelerated erosion is releasing large amounts of nutrients into the Arctic Ocean, with potential implications for carbon sequestration and marine ecosystems.
- Nature-based solutions, such as the renaturalization of floodplains and intertidal areas, are increasingly being applied to catchments and coastal regions in the northern hemisphere. While such measures can improve long-term resilience, they may lead to rapid short-term changes.

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1. Introduction

The present subchapter contains a summary of key findings published from 2018 to 2023 concerning trends and changes in erosion and sedimentation processes that might affect the world's oceans, highlighting major changes from previous World Ocean Assessments. In the first *Assessment*, key processes related to erosion and sedimentation are discussed in chapter 26. In the second *Assessment*, the topic is featured more prominently in chapter 13, which contains summaries of key findings concerning each ocean region in dedicated subsections.

Previous World Ocean Assessments have been focused mostly on coastal areas rather than erosion and sedimentation changes at sea, with a greater emphasis on erosion due to a bias in the literature. The first *Assessment* contains a detailed discussion of anthropogenic pressures, particularly the extent and impacts of land reclamation and catchment disturbances. In the second *Assessment*, emphasis is placed on global assessments of shoreline change using satellite-derived data (Luijendijk and others, 2018).

During the period covered by the third *World Ocean Assessment*, there was an increase in satellite-derived shoreline change assessments at the global, regional and local levels (Konstantinou and others, 2023; Vos and others, 2023a, 2023b; Bishop-Taylor and others, 2021; Mao and others, 2021; Konlechner and others, 2020; Mentaschi and others, 2018). Satellites can be used to bridge gaps in data availability in difficult-to-reach areas and cover large areas. However, the methods and algorithms used to extract shoreline positions vary and have intrinsic limitations (Warrick and others, 2024) that must be fully appreciated before results are used to inform policy or decision-making, particularly at the local level. It is also important to understand that magnitudes and rates of change are specific to time intervals and geographical locations, varying greatly in space and time and according to averaging and aggregation methods.

2. Environmental change since the second *World Ocean Assessment*

Pressures due to human interventions and climate change impacts continue to influence coastal erosion and sedimentation patterns (Cabana and others, 2023). Global warming is projected to exacerbate conditions along coasts due to sea-level rise and more extreme weather conditions, strengthening storm surges, winds and waves (Ewans and Jonathan, 2023; Narita and others, 2024). Such changes are discussed in detail in section 4, chapter 3, and in subsection 5B, chapter 4. Polar regions, particularly the Arctic, are fast-changing. Sea ice protects high-latitude shorelines and sediment deposited on continental shelves from wave action. In polar regions, coastal erosion results from increased wave exposure caused by reduced sea-ice cover, prolonged ice-free seasons or permafrost thaw. These effects have been linked to global warming (Cassidy and others, 2024; Irrgang and others, 2022).

Changes in wind direction and speed influence cross- and longshore currents and, by extension, sediment transport, affecting coastal erosion and sedimentation (Ibaceta and others, 2023). Coastal erosion is projected to increase in many areas due to sea-level rise and increased wave activity (López-Olmedilla and others, 2022; Ranasinghe and others, 2023; Dong and others, 2024). Potential impacts of coastal erosion include habitat, property and land loss, destruction of cultural and natural heritage, migration and other economic losses (Pouye and others, 2024; Solihuddin and others, 2024; Thepsiriamnuay and Pumijumnong, 2024), as detailed in section 4, chapter 5. On some coasts, sedimentation may increase (Anderson and others, 2022) due to sediment supplied by rivers (Yoon and others, 2023).

Coastal development disrupts or alters local sediment budget, often triggering or worsening coastal erosion (Wang and others, 2022; Saengsupavanich and others, 2024; see also subsect. 5A, chap. 9). Nature-based solutions, including restoration of mangroves (Uddin and others, 2022) and coastal marshes (Fairchild and others, 2021), have been a preferred approach (Van der Meulen and others, 2023) to mitigating coastal erosion and promoting shoreline accretion.

Changes in the overall status

Research continues to unveil the magnitude of anthropogenic disturbances on the sediment cycle and fluxes. Between 1950 and 2010, soil erosion caused by human activities more than quadrupled the mobilization of fluvial sediment, while supply from land to the coast reduced by 23%, mostly due to retention in dams (Syvitski and

others, 2022). Natural variability contributes to a very small proportion of these changes.

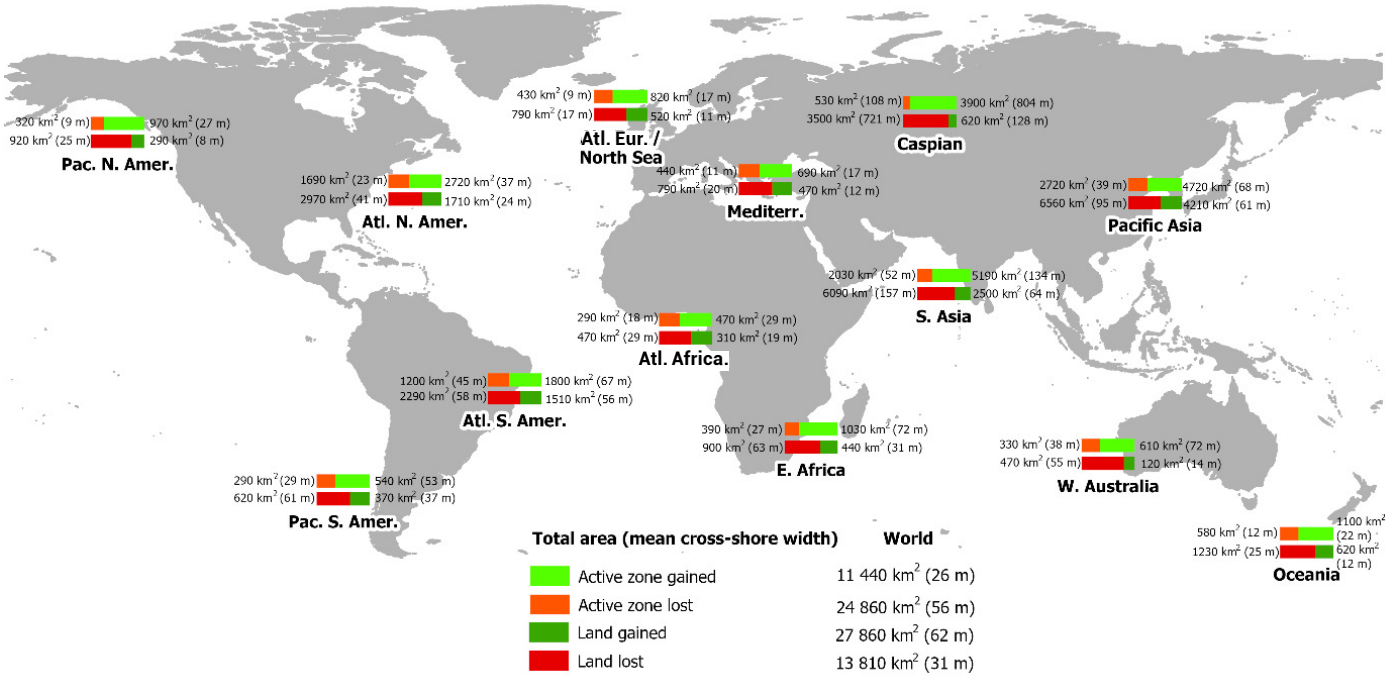
Shoreline changes are determined by regional drivers and site-specific factors, including geomorphological settings and human activities (Pang and others, 2023). Human activities areas are a main cause of the largest shoreline changes observed worldwide (Luijendijk and others, 2018; Mentaschi and others, 2018), while natural cycles, such as El Niño/Southern Oscillation (Vos and others, 2023b) and major hazards, such as cyclones and tsunamis (Bozzeda and others, 2023) can have important effects at the regional and local scales. Although global and regional assessments of shoreline change have been published, the methods used in those assessments differ, preventing comparative analysis of results.

Using satellite data but different methods, Luijendijk and others (2018) assessed sandy beaches worldwide, while Mentaschi and others (2018) covered all coastal typologies (although parts of the South-West Pacific and polar regions were excluded). The aggregated results of the former identified overall erosion for Australasia and Africa and mean accretion for other continents, while the latter reported net land loss in all continents and regions (net global loss of 14,050 km^2, see figure). Based on field data from 315 sandy beaches, Bozzeda and others (2023) indicated that 21% were intensely eroding, similar to the findings by Luijendijk and others (2018), but they diverge on the proportion of stable and accreted beaches.

Globally, there has been a transition from hard engineering solutions towards integrated, sustainable approaches that merge natural, technological and community-driven inputs. Combined with ecosystem-based management, these approaches are considered to enhance resilience to climate change impacts (Gebrael and others, 2024; van Westen and others, 2024). Arguably, this is one of the most crucial changes in recent years due to the effects on both short- and long-term local coastal responses. Growing interest in nature-based solutions stems from a better understanding of the undesired consequences of coastal engineering on natural coastal dynamics.

Figure

Mean regional losses and gains of coastal (dry) land and active (intermittently wet, including intertidal) areas and mean cross-shore width change, 1984–2015



Source: Based on satellite data; adapted from Mentaschi and others, 2018.

3. Region-specific changes

Arctic Ocean

The Arctic has warmed faster than other regions since the mid-1960s (England and others, 2021), almost four times faster than the global average over the period 1979–2021 (Rantanen and others, 2022). Sea-ice cover has been declining for the past 46 years (Irrgang and others, 2022). It is well-established that Arctic coastlines are eroding, with growing evidence suggesting acceleration. These rapid changes in the Arctic threaten settlements, infrastructure, traditional lifestyles and archaeological sites (Irrgang and others, 2022).

Nutrient and sediment fluxes are changing due to release from melting ice, eroding permafrost and increased wave interactions with the seabed. Predicting the rates and magnitudes of change is difficult (Irrgang and others, 2022) due to complex air-ice-sea interactions and the increased supply from river discharge due to land ice melt. Emerging research suggests positive feedback between carbon release from melting permafrost and global warming, as higher input of carbon into coastal waters reduces their potential to absorb atmospheric carbon (Manizza, 2024; Nielsen and others, 2022).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Erosion and sedimentation rates on the Baltic coast vary due to isostatic uplifting in the north and subsiding in the south, which contributed to accretion and erosion, respectively, at rates higher than 1 m/year over the period 2007–2017 (Weisse and others, 2021). Based on satellite data validated with field measurements, Castelle and others (2024) estimated that sandy European shores on the Atlantic accreted at a mean rate of 0.21 m/year over the period 1984–2021, although coasts exposed to high wave energy (such as those in northwest France and in Portugal) are prone to long-term erosion. The Mediterranean coast experiences moderate erosion rates of 0.4–1.0 m/year due to sea-level rise and human activity, particularly along coasts undergoing subsidence (Vecchio and others, 2024). Using satellite data from 1984 to 2017, Tătui and others (2019) reported that 68% of the Black Sea coast was stable, with erosion exceeding 1 m/year along 19% of the coast, mostly in Georgia, Romania, Ukraine and low-lying areas affected by severe storms.

South Atlantic Ocean and wider Caribbean

Studies on erosion and sedimentation changes in the South Atlantic are site-specific. The region's diverse coasts face challenges from catchment changes (Riquetti and others, 2022), limited sediment input from rivers (Oliveira and others, 2023) and beach sand extraction (Pilkey and others, 2022). Storms threaten infrastructure and populations across the region (Serafim and others, 2019; Queiroz and others, 2022; Isla and Cortizo, 2023).

In West Africa, research highlights natural and anthropogenic factors driving coastal changes mostly in Ghana, Nigeria and Senegal (Ankrah and others, 2023). Delta morphology, sedimentation, fisheries and habitats are affected by changes in river discharge and sediment supply, including in the Volta and the Niger Deltas (Ideki and Ajoku, 2024), but limited data hinder comprehensive understanding.

Caribbean small island States face coastal erosion and sedimentation issues triggered by hurricanes and sea-level rise, which reduce the natural protection offered by beaches, mangroves and reefs, as observed in The Bahamas and Jamaica (Rangel-Buitrago and others, 2018). The Caribbean Disaster Emergency Management Agency is a key player in regional risk reduction measures, including nature-based solutions (Rhiney and Baptiste, 2019).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

There is limited literature in English covering erosion and sedimentation in this diverse ocean region. Available data are mostly from local or global assessments, which limits comparative analysis. Coastal variability due to changing sediment supply from rivers has been identified in Bangladesh, India, Indonesia, Malaysia and Sri Lanka, with an increasing tendency for erosion where downstream sediment transfer is disrupted (Syvitski and others, 2022). Ecological damage to wetlands, particularly mangroves, has been linked to coastal erosion due to disruption of sediment transfers.

Impacts from human activities on erosion and sedimentation have been reported across the Indian Ocean region. Recent large-scale activities include the Mumbai Coastal Road Project in India, involving extensive land reclamation protected by a seawall (Movik and others 2023), and the Jakarta Sea Wall in Indonesia, which is an effort to

protect against the combined impacts of subsidence and climate change (Purnomo and others, 2024).

North Pacific Ocean

Coastal erosion is a constant threat in the North Pacific, especially on densely populated and economically significant coastlines (Dong and others, 2024; Siringan and others, 2024; Vitousek and others, 2023; Yum and others, 2023; Cai and others, 2022). According to the *State of the Global Climate 2023* report prepared by the World Meteorological Organization, the Pacific Ocean is experiencing rates of sea-level rise faster than the global average. Sea-level rise can trigger or increase erosion (Siringan and others, 2024; Vitousek and others, 2023), which is already a critical problem due to artificial sediment retention in many Asian rivers (Binh and others, 2020), and is exacerbated by land subsidence in some locations (Siringan and others, 2024). Studies have shown that tropical cyclones have intensified in recent decades (Li and others, 2023; Xu and others, 2024) likely due to climate change (Bloemendaal and others, 2022; Wood and others, 2023), often linked to extreme erosion events. Projections indicate that the mean wave height in the region should decrease by the end of the century (Casas-Prat and others, 2024).

Sea-level changes along the North Pacific coasts are highly affected by changes in oceanic circulation (Cha and others, 2023) and sea temperature (Ran and others, 2023). From 1960 to 2013, extreme sea-level events along the North-West Pacific coasts were 1.5 to 2 times more intense and lasted longer than the ones recorded along the eastern Pacific (Fan and Du, 2023).

South Pacific Ocean

Systematic assessments of the longer South Pacific coasts have been undertaken (Thom and others, 2018; Bishop-Taylor and others, 2021; Dickson and others, 2021; Vallarino-Castillo and others, 2024). However, the diverse morphology across the South Pacific islands confounds the characterization of erosion patterns (Nunn and others, 2020), except through aggregated assessment (Vos and others, 2023a). There is a strong awareness of erosion and land loss related to sea-level rise in the region, particularly for low-lying atolls, such as Tuvalu (Harun-al-rashid and Yang, 2023).

El Niño and La Niña have regional effects across the South Pacific (Vos and others, 2023b), influencing prevailing winds, storm incidence, sea levels and wave conditions (Vallarino-Castillo and others, 2024). More energetic conditions occur during El Niño phases in the eastern half of the South Pacific, and during La Niña in the western half, affecting the distribution of erosion pressures across the region (Ramsay, 2011; Vos and others, 2023b). In recent decades, La Niña phases have had greater influence, and, perhaps coincidentally, there have been exceptional storm events in the western South Pacific, including tropical cyclone Gabrielle in New Zealand in 2023 and multiple storms affecting the east coast of Australia from 2016 to 2024 (Turner and others, 2024).

Southern Ocean

In the Southern Ocean, ice-cover changes show high temporal and spatial variability within an overall trend of net increase over the period 1979–2020 (Reid and Massom, 2022), except on the Amundsen-Bellingshausen Seas (West Antarctica), despite an emerging positive trend since 2007 (Parkinson, 2019). Based on sea-ice extent, the maximum length of coastal exposure in Antarctica decreased 30 km per year over the period 1979–2020 (Reid and Massom, 2022). However, sea-ice cover reached record minima in February 2022, 2023 and 2024 (Riordon, 2024), remaining persistently low in recent years. It is too soon to know whether this is a temporary fluctuation (Riordon, 2024) or the inception of a new state in the Southern Ocean triggered by long-term global warming (Purich and Doddridge, 2023; Eayrs and others, 2021).

4. Key remaining knowledge and capacity gaps and new gaps

The bias in research coverage and volume persists, with large gaps in the global South, where insufficient generation, transmission and use of reliable in situ data are pervasive, despite emerging or growing research in parts of South America, Africa and South-East Asia. As nature-based risk reduction approaches become increasingly popular, a deeper understanding of the applicability of and uncertainties surrounding ecosystem-based management in different geographical contexts is required (Gracia and others, 2018; Doelle and Puthucherril, 2023). Post-erosion recovery efforts often lack sufficient research, leading to vulnerability to

future events (Garzon and others, 2024). The practice of integrating Indigenous knowledge and scientific data must be expanded to improve the understanding of site-specific socioenvironmental systems and promote cooperation among stakeholders (Loch and Riechers, 2021).

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Subchapter 6C
Marine infrastructure outside of coastal areas

Key points

- Marine infrastructure development beyond coastal areas has intensified pressures on marine ecosystems, including marine noise, seawater quality and changes to hydrodynamic circulation.
- Climate change and adaptation strategies are expected to pose significant risks to marine infrastructure.
- There has been an increasing focus on developing proactive infrastructure strategies to adapt to hazards, including nature-based solutions, buffer zones, physical barriers and systems for early warning and evacuation.
- Over the next 10 to 20 years, marine infrastructure development presents major challenges, especially with respect to climate change, but also offers opportunities for innovation, sustainable growth, enhanced security and greater resilience.

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1. Introduction

The ocean offers immense potential for clean energy, resource exploitation and food production, which has led to a surge in marine infrastructure development beyond traditional coastal areas, leading to a significant increase.

Marine infrastructure development offers opportunities to meet societal needs but poses challenges and pressures, such as the potential disruption of marine ecosystems and conflicts with existing maritime activities. Marine infrastructure, including offshore wind and subsea structures, cables, platforms and pipelines, aquaculture facilities and floating islands, exerts extensive and widespread pressures throughout its life cycle, encompassing installation, operation, maintenance and decommissioning (Dannheim and others, 2020; Coolen and others, 2020).

Marine infrastructure development beyond coastal areas has intensified, driven by technological advancements and growing demand for offshore resources (Gill and others, 2020). Marine infrastructure places significant pressure on ocean ecosystems associated with loss or disruption of natural habitats and species, alteration of oceanographic processes and ecological and geomorphic connectivity, noise and vibration generation, decline in marine biodiversity and the introduction of invasive species (Heery and others, 2017; Bishop and others, 2017; Firth and others, 2016; Chapman and Bulleri, 2003; Duarte and others, 2021a; Firth and others, 2016; Airoldi and others, 2015).

2. Changes since the publication of the second *World Ocean Assessment*

Multiple factors have contributed to changes in pressures on the open ocean in recent years. While new pressures have emerged, some align with trends previously described in the second *World Ocean Assessment*.

Since the publication of the second *World Ocean Assessment*, offshore wind farms have expanded notably, while oil and gas infrastructure development has accelerated (Jouffray and others, 2020). In addition, substantial developments have occurred in submarine cables and pipelines; there are 550 active or planned cables that span over 1.4 million km worldwide (*The Economist*, 2023). Advancements in robotics, material science and underwater communication have significantly improved the feasibility of deep-sea exploration and resource extraction, which were previously out of reach in some cases.

Meanwhile, climate change impacts have become more pronounced in the past few years. Warming seas and ocean acidification continue to negatively affect marine ecosystems, with cascading effects on human communities that rely on ocean resources (Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission), 2024; Short and others, 2021). There is growing recognition that these pressures disproportionately affect vulnerable populations, including marine communities in developing countries and small island nations, especially in polar oceans.

3. Trends in marine infrastructure outside coastal areas

According to Bugnot and others (2021) and global analyses of existing and planned marine construction and its impact on the seascape, the spread of marine infrastructure is among the most significant human alterations to global seascapes. Maps illustrating ocean industrialization at a global scale highlight shifts in some of the largest and most economically significant activities at sea (Paolo and others, 2024). The expansion of marine infrastructure beyond coastal areas represents a dynamic intersection of technological innovation, economic necessity and strategic planning.

There are ongoing efforts to develop comprehensive databases containing information on and maps of marine infrastructure. Existing online maps and databases cover different disciplinary themes, including geology, physics, energy, minerals, biology, seabed habitats, spatial planning and human activities, while also offering data and information on blue economy operations (European Marine Observation and Data Network (EMODnet), 2024; Bureau of Ocean Energy Management (BOEM), 2024; Mid-Atlantic Ocean Data Portal (MARCO), 2024; Open Infrastructure Map, 2024; European Maritime Affairs, 2024).

Marine energy infrastructure

The evolution of the offshore oil and gas sector has been complex, with some regions shifting towards

decommissioning while others expand exploration (Shaffer, 2020). Oil and gas platforms are usually located on the continental shelf, but technological advances have enabled drilling in deeper waters, such as those in the Gulf of Mexico, the North Sea and off the coast of Brazil (Zou and others, 2021; Dou and others, 2022; Wen and others, 2023) and other operations in more challenging environments. The oil and gas industry has the potential to play a significant role in the sustainable energy transition.

Offshore wind energy has grown remarkably, as larger turbines have been deployed further offshore. Wind farms are typically located in shallow waters up to 50 m deep, but their installation has been moved further offshore to capture stronger and more consistent wind resources. Floating wind farms are also being developed for deeper waters, including those in the North Sea (Guşatu and others, 2021) and along the Atlantic coast of the United States (Baker and others, 2024; Shields and others, 2023). However, better planning and optimization of locations are required to induce the modification of atmospheric dynamics and, consequently, wind speed reductions (extending as far as more than 40 km downwind from the farm) (Akhtar and others, 2021). The countries that have the most consistent environmental and regulatory policies and that have a tendency to use renewable-energy technologies have been the fastest to implement these wind turbines (Long, 2014). The areas with the greatest potential for offshore wind energy production are located mainly in Asia (on the China Sea) and Europe (on the North Sea, western part of the Baltic Sea and East Atlantic) (Enevoldsen and Jacobson, 2021).

Wave and tidal energy installations are placed in areas with strong tidal currents and significant wave activity, often near the coast but sometimes further out to harness stronger resources (Khojasteh and others, 2023). Progress has been made on tidal energy projects, and several commercial-scale installations are now operational. Wave energy converters represent a promising technology for future deployment (Neill and others, 2017).

Shipping and navigation infrastructure

Deepwater ports are located further offshore to accommodate large vessels that cannot navigate closer due to depth constraints. Transoceanic shipping routes have led to the development of infrastructure supporting shipping lanes that traverse open oceans, including emergency response facilities. Seaports, due to their strategic locations and infrastructure, are emerging as pivotal hubs for the production, storage and distribution of green hydrogen (Notteboom and Haralambides, 2023).

Subsea cables and pipelines

Subsea communication cables are used to respond to the demand for global connectivity, which leads to extensive networks of submarine cables crossing ocean basins. Subsea cable installations have increased significantly, forming a critical part of global communications infrastructure (TeleGeography, 2023). A systematic review of the current security threats to the European Union subsea data cable network (Bueger and others, 2022) contains several recommendations on how to improve the resilience of the network. Oil and gas pipelines connecting offshore platforms to coastal refineries and distribution networks usually follow the most direct and safest route along the seabed. The development of renewable marine infrastructure requires the development of new routes for power transmission cables to connect offshore renewable-energy sources to onshore grids (Cullinane and others, 2022). Recent incidents involving cable damage and geopolitical tensions have led to a greater emphasis on safeguarding undersea infrastructure. For example, naval exercises have been conducted specifically to protect submarine cables and pipelines (National Oceanic and Atmospheric Administration (NOAA), 2024).

Other technologies

With advancements in underwater technology, there is increasing interest in mining the deep seabed for minerals, including polymetallic nodules, cobalt and rare earth elements, particularly in the Clarion-Clipperton Zone in the Pacific Ocean. Offshore aquaculture has also expanded significantly, with larger fish farms deployed further offshore (Gentry and others, 2017). Combining energy production, food systems and resource extraction within shared offshore spaces is a common future pathway globally (Depellegrin and others, 2019). One growing trend involves the utilization of multi-use platforms combining different industries, such as offshore energy production (wind, solar or tidal) with aquaculture and desalination plants.

4. Interactions with and effects on marine ecosystems and human well-being

Marine infrastructure interacts with ecosystems on multiple temporal scales. Short-term construction activities cause immediate disturbances, while long-term interactions involve changes to ecosystem structure and function (Dannheim and others, 2020). Infrastructure significantly impacts seabed ecosystems but may also increase habitat heterogeneity (Coolen and others, 2020). Increased underwater noise pollution affects marine life behaviour and physiology (Nowacek and others, 2015). Large-scale infrastructure can alter local hydrodynamics, potentially affecting sediment transport and larval dispersal (van Berkel and others, 2020). Socioeconomic impacts include job creation and the potential disruption of traditional maritime activities (Hooper and others, 2015). The expansion of marine infrastructure has implications for human health, both positive and potentially negative (Buonocore and others, 2016).

Far-field marine noise

Ocean noise perturbs the oceanic environment and impacts marine life to an extent that is still not completely understood (Duarte and others, 2021a). Some species are more sensitive to short but powerful impulsive bursts, while others are deeply affected by continuous low power disturbances (Merchant and others, 2020). Depending on the power and frequency of noise and the physical properties of the ocean, acoustic waves can propagate rapidly to long distances (Jensen and others, 1994; Nieukirk and others, 2004). While the noise generated by offshore infrastructure is only one component of overall anthropogenic noise (Sirovic and others, 2021), it is an important one because of its persistence.

The noise generated by offshore infrastructure can be categorized according to three phases of the infrastructure life cycle: installation, operation and decommissioning. Depending on the specific type of infrastructure, installation may involve the bottom fixing or bottom laying of cables or pipes (Jiang, 2021). Preparatory work generally encompasses careful sounding of the bottom and sub-bottom, which often requires extensive light seismic surveys at the site and on the route to the site (Duarte and others, 2017). The sound sources used in such surveys can be very harmful for sensitive species at the local or regional level (Duarte and others, 2021b; Spadoni and others, 2023). During installation, pile driving and dredging are the most common sources of noise (Amaral and others, 2020).

During the operation phase, underwater noise is generated by structural moving parts, turning engines and other specific sound-emitting machinery. Machinery, turbines and other engines above water transmit vibrations through the submerged supporting structure or through the water interface. Although levels are low relative to shipping noise, underwater noise from wind farms can be substantially higher (Tougaard and others, 2020). Offshore infrastructure also generates a significant acoustic particle acceleration signature that is highly disturbing for species living near the ocean bottom, the sea surface and the infrastructure that supports wind turbines (Sigray and Andersson, 2011) and marine energy converters (Popper and others, 2023).

Wave and current circulation patterns

Hydrocarbon extraction platforms and subsea infrastructure can modify local hydrodynamics by creating physical barriers that affect sediment transport and coastal erosion processes (Erikson and others, 2022). Offshore aquaculture installations similarly affect local water flow and wave patterns, affecting nutrient distribution and sedimentation in the surrounding areas (Wang and others, 2021).

Seawater quality and marine mammals

Hydrocarbon extraction can lead to water pollution through oil spills, drilling muds and produced water discharge, which can contain hydrocarbons and heavy metals, affecting seawater quality and impacting the food chain (Erikson and others, 2022). Marine renewable-energy devices generally have less severe impacts, although they can release anti-fouling agents and other chemicals used to maintain equipment (International Energy Agency (IEA), 2019). Offshore aquaculture can cause nutrient enrichment and organic matter accumulation, potentially leading to eutrophication and harmful algal blooms, thereby degrading water quality (Wang and others, 2021).

Marine mammals can be affected by offshore activities, primarily through noise pollution, physical barriers and water quality degradation. Noise from hydrocarbons extraction and renewable-energy installations can disrupt marine mammal behaviour and communication (Erikson and others, 2022; International Energy Agency, 2019). Offshore aquaculture poses entanglement risks and disrupts natural foraging patterns and habitats (Wang and

others, 2021). Undersea cables, although less impactful, generate electromagnetic fields that can affect marine mammals, especially when high voltages are involved.

Seabed interaction

Deep seabed mining generates negative impacts to human health through three possible pathways, most importantly through its impacts on fish stocks and fisheries. Semi-permanent ships, support platforms and riser pipes transporting mined minerals may interrupt fish migration due to light and noise pollution. The collective impact on global fisheries has repercussions for food security, especially for Indigenous Peoples and local communities that are highly dependent on the marine ecosystem as their main source of nutrition (Hamley, 2022). Moreover, increased ambient concentrations of metals, such as copper, lead, zinc, cadmium and rare earth metals, in marine ecosystems may accumulate and enter the human food web (Hauton and others, 2017). There is concern that seabed mining will disturb and resuspend seabed sediments, potentially releasing sequestered carbon (Hamley, 2022).

Health and well-being

Marine infrastructure is vital to advancing national economic and security interests. Improving marine infrastructure, such as seaports and shipyards, could improve human well-being by reducing consumer prices, creating new jobs and assisting local communities in marketing their seafood and farming products to other areas. However, marine infrastructure planning and development is often marked by a failure to include Indigenous Peoples and local communities in decision-making processes and to consider the environmental impacts on neighbouring coastal communities and ecosystems (Morgera, 2024; Morgera and Lily, 2022). Environmental impact assessments are undertaken on a project-specific basis, without consideration being given to the dynamic nature of ocean and coastal ecosystems and without an assessment of the cumulative impacts associated with marine infrastructure developments (Sunde, 2022).

5. Conclusion

Marine infrastructure development outside coastal areas has intensified, introducing new pressures on marine ecosystems. While offering economic benefits and potential contributions to sustainable energy and food production, such development presents complex challenges for marine ecosystem health and ocean governance. Primarily, climate change, adaptation strategies and resilience reflected by rising sea levels and more frequent extreme weather events are expected to pose significant risks to marine infrastructure (Talukder and others, 2022).

The advantages of deploying environmentally friendly emerging technologies whose benefits are demonstrated by relevant extensive life-cycle analyses across the entire life cycle of marine infrastructure could contribute significantly to the predicted technological and economic benefits and to sustainable energy. Many Governments are adopting more integrated approaches to marine management, considering the interconnections between land and marine use, development, natural hazards and environmental protection (Eger and others, 2021).

There is an increasing focus on developing proactive infrastructure strategies to adapt to hazards, which may include nature-based solutions, buffer zones, physical barriers like seawalls, retreat and protect approaches, and systems for early warning and evacuations. While developed nations focus on adaptation and resilience, many developing countries may struggle with basic marine infrastructure needs, potentially widening the global infrastructure gap.

Over the next 10 to 20 years, marine infrastructure poses significant challenges, particularly from a climate change perspective, but also presents opportunities for innovation, sustainable development, security and improved resilience. Proactive planning, substantial investment and effective collaboration between government bodies, industries and communities are required to minimize pressures from marine infrastructure.

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Subchapter 6D
Cumulative effects

Key points

- Cumulative effects assessments, also known as cumulative impact assessments, have been applied continuously since the publication of the second *World Ocean Assessment*.
- These assessments are being used within national jurisdictions to inform decision-making.
- Lessons learned from the application of cumulative effects assessment can guide further development of assessment approaches.

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1. Introduction

Approaches to cumulative effects assessments were reviewed in the second *World Ocean Assessment*. In the development of such assessments, consideration needs to be given to the scale and resolution at which the assessment is being conducted, the values being assessed, the data available, the uncertainties associated with the data and the management objective. The conclusions reached in the second *Assessment* included that expert knowledge and qualitative data were moderately used across assessments, that geographic information systems were commonly used, that uncertainty was rarely evaluated and that integrative methods were increasingly being developed.

According to the second *World Ocean Assessment*, a cumulative effects assessment consists of the following key functional steps:

- Definition of the values of the marine system being assessed
- Definition of the activities that place pressures on the marine system (stressors)
- Conceptual linking of pressures and values
- Assessment of risk and uncertainty
- Validation.

In the second *World Ocean Assessment*, attention was drawn to the following key areas where improvements to cumulative effects assessments were needed:

- Incorporation of the extent and spatial and temporal variability of data and their associated uncertainty
- Enhancement of experiment-based and observation-based methods for assessing the sensitivity of ecosystem components to the impacts of stressors
- Incorporation of repeated temporal studies
- Strengthening of connections between cumulative effects assessments and the management measures designed to regulate pressure-inducing activities
- Consideration of the spatial separation between the activity location and the pressure effect
- Clearer definition of the causes and consequences of harmful effects
- Development of approaches that can be applied in developing economies.

2. Changes since the second *World Ocean Assessment*

Since the publication of the second *World Ocean Assessment*, there has been increasing acceptance of cumulative effects assessments and cumulative impacts assessments as structured processes (Piet and others, 2021) that serve to specify the functional relationships between human activities, the associated pressures and the state of the ecosystem (Stelzenmüller and others, 2020). Only recently have linkages been drawn between the ecosystem components assessed in a cumulative effects assessment and their contribution to ecosystem services (Ruskule and others, 2023; Simeoni and others, 2023). Particularly in European seas, there is increasing recognition of the need to align the boundaries of cumulative effects assessments with the areas where the operational modes of human activities are regulated through marine spatial planning processes (Hammar and others, 2020; Kirkfeldt and Andersen, 2021). Nevertheless, there is rarely any exploration of future trajectories of human activities and marine spatial planning and how those trajectories might influence outcomes of such assessments in the future (Stelzenmüller and others, 2024). In many regions, cumulative effects assessments have not yet been integrated into management frameworks.

In transboundary settings such as Europe (Mackelworth and others, 2024) and the Yellow Sea (Ma and others, 2023), socioeconomic interests are confined to national boundaries, but ecosystem health and resilience depend on ecosystem processes and exposure to human pressures at multiple spatial and temporal scales (Elliott and others, 2023). Some marine spatial planning processes require international consultations, which increases the complexity of determining effective management responses to mitigate unwanted adverse effects (Cormier and others, 2018).

Mitigating undesirable effects, particularly at multiple spatial scales, requires management responses involving a series of measures. In practice, this means integrating environmental impact assessments for local projects, such as offshore wind farms (Oh and others, 2021), with regional environmental assessments for marine spatial planning (Cormier and others, 2022; Kirkfeldt and Andersen, 2021) and regional sea assessments. While

cumulative effects assessments have been used extensively in Europe, they are less common in other regions (see the case studies on South Africa and Australia, below).

The integration of cumulative effects assessments into jurisdictional decision-making is an increasingly common practice, though progress has been slow, and such assessments have become policy documents. The present update is focused on where that transition is in process or has been made. Case studies that illustrate various policy applications of cumulative effects assessments in some jurisdictions since the publication of the second *World Ocean Assessment* are further detailed below.

3. Region-specific changes

Case study: South Africa

Compiling data and undertaking analysis for cumulative impacts assessments and other assessments of the state of marine ecosystems can be particularly difficult for developing countries, where data and capacity are more limited. South Africa is one of the few developing countries that have undertaken cumulative marine pressure mapping as part of its National Biodiversity Assessment, which is conducted every five to seven years. In the 2018 Assessment, 31 pressures on marine biodiversity were mapped (Sink and others, 2019), and additional pressures have been mapped for the 2025 assessment. A cumulative pressure map is used to develop a national map of ecosystem degradation, which is overlaid on an iteratively improving national map of marine ecosystem types to assess ecosystem threat status using an approach aligned with ecosystem red-listing standards developed by the International Union for Conservation of Nature (IUCN) (Keith and others, 2013). These products are used in policymaking, spatial planning and systematic conservation planning to support the expansion of marine protected areas (MPAs) (Sink and others, 2023b; South African National Biodiversity Institute and United Nations Environment Programme World Conservation Monitoring Centre (SANBI and UNEP-WCMC), 2024).

The purpose of cumulative pressure mapping in South Africa is to produce a map of ecosystem conditions to determine the amount and location of remaining natural areas and their condition in terms of how their composition, structure and function have been modified from a "natural" reference condition. South Africa mapped and evaluated 31 different pressures individually and cumulatively as a surrogate for ecosystem degradation. The extent and intensity of pressures were considered, together with an expert-derived impact score that accounted for different combinations of pressures and ecosystem types (Sink and others, 2019). An ecosystem condition map was produced, with degradation assessed in four categories aligned with IUCN red-listing criteria for degradation (criteria C and D).

Building on the National Biodiversity Assessment, Skein and others (2022) drew from the cumulative pressure mapping and reports to undertake a scoping exercise for an integrated ecosystem assessment, considering 17 sectors, 17 key pressures, 23 key ecosystem characteristics and 23 ecosystem services. They noted that fishing, petroleum activities and shipping were widespread sectors resulting in many pressures on multiple ecosystem components and discussed the many interacting pressures that cumulatively affect South African marine ecosystems. Smit and others (2024) conducted the first ground truthing of marine ecosystem conditions in South Africa and showed that while pressure mapping was an effective proxy at broad national scales, updated and finer-scale pressure mapping was needed to improve condition estimates. When planning and management decisions are based solely on cumulative impact scores, the actual condition of the environment may be misrepresented, especially at finer scales. Although South Africa has made progress with cumulative pressure mapping, there is a need to increase mapping, modelling and analysis capacity, account for non-linear, synergistic and antagonistic interactions among stressors and ground truth ecosystem conditions across multiple ecosystem functional groups. Failure to accurately map pressures and account for cumulative impacts will mean that potential impacts are missed and will increase the likeliness of poor spatial planning and decisions with negative impacts on people and the environment.

Case study: Mediterranean Sea

The Mediterranean Sea is the largest and deepest enclosed sea on Earth and a known biodiversity hotspot. The first cumulative effects assessment studies conducted in the early 2000s already contained reports of widespread and severe effects in both the western and

eastern Mediterranean basins (Coll and others, 2012; Micheli and others, 2013). Pollution and widespread coastal development were identified as the two main pressures. That pattern remains consistent, as the Adriatic Sea and the western Mediterranean have been identified as the two areas in Europe with the most severe cumulative effects in the coastal and shelf areas owing to several anthropogenic pressures, particularly physical loss and disturbance due to intensive fishing, pollution and coastal activities (European Environment Agency (EEA), 2019). Across the entire basin, long-standing overexploitation of fish stocks (especially in narrow shelfs), marine litter, strong rates of warming and heatwaves and the high number of non-indigenous species (NIS), particularly in the eastern Mediterranean, are also generalized patterns (European Topic Centre on Inland, Coastal and Marine Waters (ETC/ICM), 2019).

In terms of species and ecosystem responses to cumulative effects, most studies over large scales assess the impact of a limited number of pressures (mainly climate and fishing impacts), with diversity synergistic or antagonistic responses across species and ecoregions over the entire basin (Coll and others, 2016; Corrales and others, 2018; Moullec and others, 2023). Many studies have also reported long-standing anthropogenic erosion of population and ecosystem resilience, which has triggered and heightened sensitivity to natural environmental variability (Fu and others, 2020; Hidalgo and others, 2011, 2022). Benthic habitats and associated vulnerable species, such as coralligenous species, have been shown to be sensitive to impacts, particularly to local anthropogenic impacts associated with coastal development (Bevilacqua and others, 2018). Mortality events of these marine forests are often associated with heatwave events in areas with high cumulative impacts (Garrabou and others, 2022; Canessa and others, 2024). In the eastern Mediterranean, cumulative scenarios suggest that the beneficial effects of regulating fishing efforts may be dampened by the impact of strong warming and alien species when acting together (Corrales and others, 2018). Spatial erosion of communities due to cumulative impacts is also increasing the heterogeneity of local and sub-regional ecosystem responses to warming and other impacts, disrupting natural biodiversity gradients as well (Pennino and others, 2024). Major data gaps have been identified in cumulative effects assessments in the Mediterranean Sea and the Black Sea, particularly with respect to offshore measurements and open sharing of national indicator threshold values (ETC/ICM, 2019). Knowledge gaps on marine litter, a well-established pressure, are being rapidly filled through recent efforts to develop monitoring and forecasting tools (Galli and others, 2023).

Case study: Baltic Sea

As part of the *State of the Baltic Sea 2023: Third HELCOM Holistic Assessment 2016–2021*, which included an extensive evaluation of the ecosystem health of the Baltic Sea over that period, the spatial distribution of pressure and impact assessment developed by the Baltic Marine Environment Protection Commission (HELCOM) was used to examine how human activities generated pressures on ecosystem components, such as species and habitats. By linking spatial data on ecosystem components with pressures, it served to identify overlaps and assess the sensitivity of ecosystems to specific pressures. This approach helped trace which activities drove the impacts and provided insights into the relative impact levels across the region. While the spatial distribution of pressure and impact assessment was used to support holistic assessments of the Baltic Sea, it did not quantify absolute pressure or impact magnitudes, nor did it function as a status assessment like the Water Framework Directive. Moreover, the spatial distribution of pressure and impact assessment was limited to expert knowledge and simplified pressure-response systems, and thus cumulative impacts were treated as the sum of individual pressures while synergistic interactions between them were overlooked. This limitation generates biases in ecosystem-based management of human activities at sea, threatening the achievement of environmental and socioeconomic sustainability goals.

Nevertheless, a substantial body of scientific literature has been developed, exploring both the separate and interactive effects of multiple pressures on diverse ecosystem assets and services. This enables a shift away from expert-based cumulative effects assessments towards assessments with data-driven approaches, allowing for the inclusion of more complex responses to various pressures. The recently developed PlanWise4Blue tool introduces a methodology for cumulative effects assessments in which scientific evidence is combined with expert judgment and presented using an interactive online tool for environmental managers (Kotta and others, 2020). The tool's knowledge matrix, which is based on cause-effect data, quantifies both single and synergistic effects of key human activities on a wide range of nature assets, providing real-world metrics (such as species biomass or habitat loss or gain) under different

scenarios instead of arbitrary indices. While some impact coefficients still rely on expert judgment, empirical data will be increasingly incorporated into the tool as it becomes available. The free-to-use tool is designed for marine managers and policymakers without scientific backgrounds, offering user-friendly access to the best available data for decision-making.

The tool has been used for maritime spatial planning in Estonia to evaluate environmental sustainability and is fully functional across the Baltic Sea, with plans for expansion to other marine systems (Vaher and others, 2022). Future versions will feature an artificial intelligence-driven multimodal information retrieval system, capable of extracting and processing impact-related data from scientific publications and integrating such data into predictive models.

Case study: Australia

The cumulative effects assessment has been identified as an important part of environmental management under the Environmental Protection and Biodiversity Conservation Act of 1999. While the Act provides for broad regional assessments of cumulative effects, it does not explicitly require cumulative effects assessments as they are commonly understood in the scientific literature (Dales, 2011; Dunstan and others, 2020, 2023; Hayes and others, 2021; Ostwald and others, 2021). The lack of a formal regulatory framework in Australia for cumulative effects assessments notwithstanding, there has been an increasing number of cumulative effects assessments at both the local (Fulton and others, 2017) and regional scales (Hayes and others, 2021). These assessments have been developed by the scientific community in collaboration with proponents of such assessments and government agencies as part of strategic, regional or national assessments.

Notable examples of regional or strategic cumulative effects assessments include the *NSW Marine Estate Management Strategy 2018–2028* (Marine State Management Authority (MEMA), 2018), the *Marine and Coastal Policy* of the State of Victoria (Department of Environment, Land, Water and Planning (DELWP), 2020) and the cumulative effects assessments prepared for the Spencer Gulf (Gillanders and others, 2016), Gladstone Harbour (Eco Logical Australia, 2019; Fulton and others, 2017), the Great Barrier Reef (Dunstan and others, 2020), the Gascoyne Region (Fulton and others, 2015) and the Kimberley Region (Boschetti and others, 2020). The approaches applied in such assessments vary from the typical spatial additive assessment frameworks (Halpern and others, 2008; Stelzenmüller and others, 2018; Hayes and others, 2021; Dunstan and others, 2023), which calculate the sum of the direct effects on ecosystems, to more strategic, quantitative ecosystem-based assessments that explicitly address non-additive and non-linear combinations of effects through the entire ecosystem (Fulton and others, 2015, 2017; Boschetti and others, 2020).

At the national level, the approach set out in the Parks Australia monitoring, evaluation, reporting and improvement framework (Hayes and others, 2021; Dunstan and others, 2023) included a spatial additive assessment of cumulative impacts across the exclusive economic zone (EEZ) of Australia, based on 39 identified activities that were expected to alter the natural state of the country's marine ecosystems. A cumulative effects assessment was used to prioritize the locations of monitoring efforts in Commonwealth marine reserves to test the effectiveness of management. Recently, an Australia-wide cumulative effects assessment focused specifically on the effects of commercial, recreational and customary fisheries on at-risk species in State and Commonwealth jurisdictions was completed (Fulton and others, 2023). The approach used entailed a hierarchical cumulative effects assessment, in which a spatial cumulative additive fishing pressure map based on 409 species that commonly interact with Australian fisheries was implemented (see sect. 4, subchap. 6E, figure I). A key aspect of the hierarchical cumulative effects assessment framework is to move to a quantitative ecosystem model approach in areas where species have been identified as being at higher risk due to spatial cumulative effect hotspots. Then, more specific modelling approaches that deal with ecosystem dynamics between effects and ecosystem values can be developed for such areas, with a view to building a more strategic management framework for high-risk regions. Lastly, as part of the National Climate Risk Assessment, a cumulative effects assessment on the impact of key climate hazards on the country's marine ecosystems was developed. The assessment looked at the trajectories of relative ecosystem risk under different global warming levels to identify which parts of the country's EEZ are most at risk from near-term (global warming level 1.5°C) and long-term (global warming level 3.0°C) climate impacts.

4. Key remaining knowledge and capacity gaps and new gaps

It is necessary to jointly develop global platforms that can be used to map human pressures and natural assets, as well as a knowledge base that can be used to predict the potential effects of different combinations of human pressures on such assets. Such platforms should not only enable the assessment of the effects of current pressures but also offer capacity for scenario analysis, thereby helping to prevent unnecessary damage to ecosystems. The pressures that are considered in cumulative effects assessments vary in spatial footprint. Effects such as fishing and infrastructure have a clear spatial footprint and generate impacts on a local scale, while others related to climate change, such as warming, generate impacts over regional or larger scales. Ecosystem responses are often context-dependent; the responses to a given pressure or combination of pressures may not be identical in all places. Activities and stressor footprints do not necessarily inform on the population and ecosystem responses, which often occupy different space and timescales (Low and others, 2023).

Ecosystem responses can be observed at both a larger and a smaller scale than the stressor footprint. In addition, changes in ecosystem structure and species abundance response can often be seen away from the activity footprint, triggering asynoptic effects on ecosystems, as typically observed in river run-off or localized pollution sources. Temporal mismatches between stressor addition and ecosystem responses are also generated by legacies and carry-over effects (Low and others, 2023). For instance, a large response footprint to a stressor can occur if the ecosystem response persists for longer than the stressor or if ecosystems do not recover after stressor cessation (i.e. a legacy remains) or due to carry-over effects of stressors on future life stages of, for example, anadromous or migratory species. Differential spatial and temporal degradation can result in patchy ecosystem responses. In addition, natural variation in seascape characteristics may result in some areas being more sensitive to similar effects. In such cases, dispersal and ecological connectivity can help to mitigate spatially heterogeneous cumulative disturbances, such as spatial insurances (Loreau and others, 2023). The way in which the components of ecological systems are spatially and temporally connected and distributed is critical for withstanding the cumulative combination of natural and anthropogenic disturbances and therefore is fundamental for resilience. Marine connectivity plays a pivotal role in supporting resilience (Hilty and others, 2020; Pearson and others, 2021), but how this influence is mediated and which are the mechanisms of action are still poorly understood.



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Subchapter 6E Pollution

Key points

- Chemicals and other materials from land-based sources continue to impact ocean ecosystems.
- There has been a decline in mercury emissions and precipitation, along with reductions in emissions to air of some organic compounds, in certain regions.
- Growing demand for non-carbon electricity has resulted in an increased reliance on nuclear power, which is likely to lead to higher radioactive discharges.
- Persistent organic pollutants (POPs) continue to impact all ocean regions, including polar regions and the deep sea, as well as coastal marine ecosystems.
- Toxicity studies indicate that pharmaceuticals and personal care products (PPCPs) have significant adverse effects on marine organisms, including behavioural changes in fish, invertebrates and algae.
- Global plastic waste emissions continue to rise, with substantial leakage due to mismanaged waste, microplastic abrasion and loss, littering and marine activities. These plastics, especially microplastics, impact all marine ecosystems, with over 4,000 species affected.

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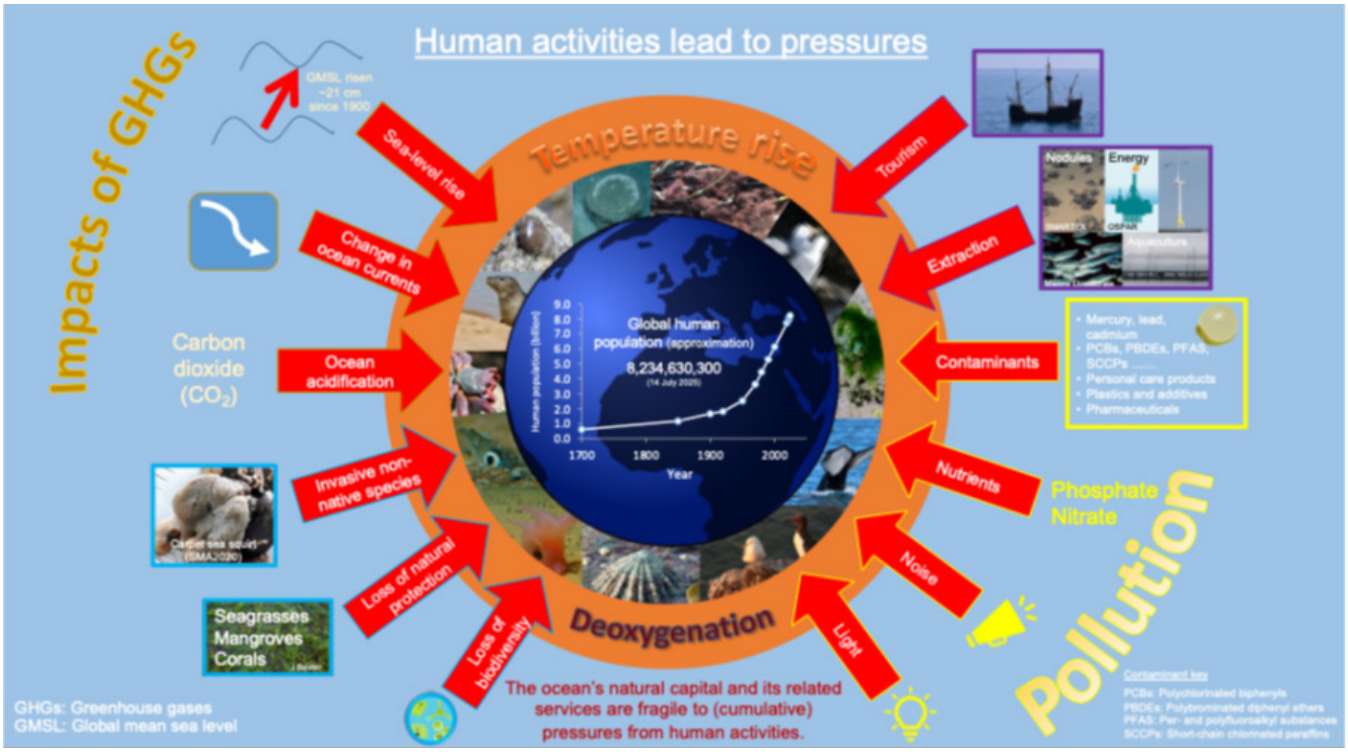
1. Introduction

Human activities generate multiple pollutants, including pharmaceuticals, heavy metals, organic compounds, radioactive materials, plastics and plastics additives, sediments, nutrients, pathogens, energy (heat, light and noise) and numerous other contaminants of emerging concern. The focus of the present subchapter is initially inputs of heavy metals and selected contaminants from the atmosphere and rivers. This is followed by a more in-depth discussion of the concentrations and effects of POPs, pharmaceuticals, personal care products, plastics and plastics additives and radioisotopes. Many of these compounds and materials ultimately reach the ocean through atmospheric transfer and deposition, general land run-off, rivers, storm overflows and sea-based activities. These pollutants may subsequently be transported more widely by ocean currents. As a result, marine biota are exposed to numerous chemicals, many of which have physiological effects. Alongside biodiversity loss and rising concentrations of greenhouse gases, such as carbon dioxide (CO_2), methane and nitrous oxide, pollutants further intensify an already precarious multiple stressor scenario for marine ecosystems (see figure I).

The present subchapter provides an update to the information contained in the second *World Ocean Assessment* on the concentrations and consequences of POPs, plastic products and additives, pharmaceuticals, personal care products and radioisotopes on the ocean and the marine organisms that live in, on or near the ocean. This is coupled with recent developments in the understanding of the atmospheric inputs of a range of chemicals to the ocean. While the materials and chemicals covered are similar to those described in the second *Assessment*, greater emphasis is placed on per- and polyfluoroalkyl substances (PFAS), and PPCPs are discussed in greater depth.

Figure I

Pressures from, and of, human activity on marine ecosystems



Source: Prepared by the writing team. World population data from Worldometer. Images of polymetallic nodules and the "Barbie Pig" are courtesy of the National Oceanography Centre and the Trustees of the Natural History Museum of the United Kingdom, with acknowledgement to the Natural Environment Research Council's Seabed Mining and Resilience to Experimental Impact (SMARTEX) project. Images of the sand eel and deep-sea sponge are courtesy of the Scottish Marine Directorate.

Note: The presence of pollutants further exacerbates an already precarious multiple stressor situation for marine ecosystems.

Abbreviations: GHGs, greenhouse gases; GMSL, global mean sea level; PBDE, polybrominated diphenyl ether; PCB, polychlorinated biphenyls; PFAS, per- and polyfluoroalkyl substances; SCCP, short-chain chlorinated paraffins; SMA2020, Scotland's Marine Assessment 2020.

2. Recent developments in atmospheric and riverine inputs

Key points

- Both atmospheric deposition and riverine inputs remain important pathways through which contaminants, including plastics, reach the ocean.
- Nevertheless, there has been a decline in air emissions of heavy metals and some legacy POPs from western Europe.

Contaminants continue to be distributed globally

Long-range atmospheric transport continues to be a key process by which pollutants move around the planet. As a result, pollutants impact marine organisms a considerable distance from their sources of emission. Long-range atmospheric transport is a key driver behind pollutants that are detected in the polar regions and the deep ocean, including the Mariana Trench (Dasgupta and others, 2018). In the deep ocean, ocean currents are another key driver. Chlorinated paraffins have been detected in deep-sea cold seep ecosystems, where they have been bioaccumulated by deep-sea mussels (Lyu and others, 2023). In deep-sea sediments from the western Pacific Ocean, concentrations of some POPs, including polychlorinated biphenyls (PCBs) and dicofol, were low or the compounds were not detected. In the same samples, however, polycyclic aromatic hydrocarbons (PAHs) were detected at concentrations between 5.2 and 24.5 nanograms per gram (ng/g) dry weight. Biomass and coal combustion have been identified as the predominant sources of PAHs, which indicates atmospheric deposition (Ge and others, 2021).

Per- and polyfluoroalkyl substances

Interest in per- and polyfluoroalkyl substances (PFAS) has grown in recent years. More details about concentrations and impacts of PFAS can be found under "Persistent organic pollutants" below. Determining the source of these compounds is important. An analysis of an ice core from Devon Island, Nunavut, in northern Canada revealed continuous and increasing deposition of perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) over the period 1977–2015. North American and Eurasian emission sources, particularly sources in Continental Asia, were large contributors (Pickard and others, 2018).

In some cases, riverine inputs remain critical. For example, the riverine input of perfluorooctanesulfonic acid (PFOS) to the Baltic Sea exceeds atmospheric input by a factor of three. In other cases, such as with perfluorooctanoic acid (PFOA) and other PFCAs, atmospheric deposition makes a higher contribution to the total inputs to the Baltic Sea (Johansson and Undeman, 2020). Potential sources of the loading of PFOS and other PFAS in rivers in the Baltic Sea region include discharges from wastewater treatment plants, atmospheric deposition to catchment areas and run-off from contaminated sites (Baltic Marine Environment Protection Commission (HELCOM), 2020). The relative contribution probably varies from river to river.

Atmospheric deposition can be dry or wet. In their study on four perfluoroalkyl acids (PFOS, PFOA, perfluorohexane sulfonic acid (PFHxS), and perfluorononanoic acid (PFNA)), Cousins and others (2022) concluded that:

- Levels of PFOA and PFOS in rainwater often greatly exceed the lifetime drinking water health advisory levels established by the Environmental Protection Agency of the United States of America.
- The sum of those four perfluoroalkyl acids in rainwater is often above Danish drinking water limit values.
- Levels of PFOS in rainwater are often above the European Union environmental quality standard for inland surface waters.
- Atmospheric deposition leads to contamination of global soils.

Pharmaceuticals

Mass consumption of certain pharmaceuticals has led to a greater concentration of pharmaceutical residues in aquatic environments and river discharges. Septic tanks are also a pathway for emerging contaminants, including different analgesics, antihistamines, antidepressants, beta blockers and the antidiabetic drug metformin, entering the aquatic environment (Wilschnak and others, 2024).

Declines in emissions and deposition of contaminants are happening

Humans have become acutely aware of the risks associated with both organic and inorganic contaminants. Actions have been and continue to be taken to limit emissions and discharges of contaminants. These actions are having an impact (see box 1).

Box 1

Case study: declines in emissions and deposition of heavy metals and selected organic contaminants

Mercury in air, precipitation and emissions to the air from European Union countries decreased by, respectively, 1.3%, 3.0% and 3.2% annually, over the period 2010–2022 (Gauss and others, 2024). Declines during that period were higher than those recorded during the period 2000–2010. European emissions declined faster than concentration levels in air, showing the influence of long-range atmospheric transport on mercury air concentration.

In the western region of the European Monitoring and Evaluation Programme (EMEP), which covers western Europe, emissions to air of cadmium, mercury and lead declined over the period 2000–2022, as did emissions to air of polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), hexachlorobenzene (HCB), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs). In the eastern region, which covers eastern Europe, the Caucasus and Central Asia, emission trends are not completely evident, mainly due to incomplete reporting by major emitting countries.

An example of a decrease in deposition was noted for the Baltic Sea where the deposition of mercury, lead, cadmium and benzo[a]pyrene has decreased steadily since 1990 (Gauss and others, 2024).

3. Persistent organic pollutants

Key points

- POPs remain a global problem due to their persistence, bioaccumulation and health risks.
- POPs, including emerging ones such as PFAS, and replacement chemicals, including polyhalogenated carbazoles (PHCZs), are gaining increasing attention because their environmental and public health impact continues to be exacerbated by inadequate waste management, climate change-related remobilization of POPs that have been trapped in water, ice sediments and soil for decades, and inconsistent global enforcement of international agreements despite international efforts to eliminate their sources.
- Although POPs are yet another anthropogenic pressure on the ocean, adding to the stress on biological systems, there is some indication that concentrations of some legacy compounds are decreasing.

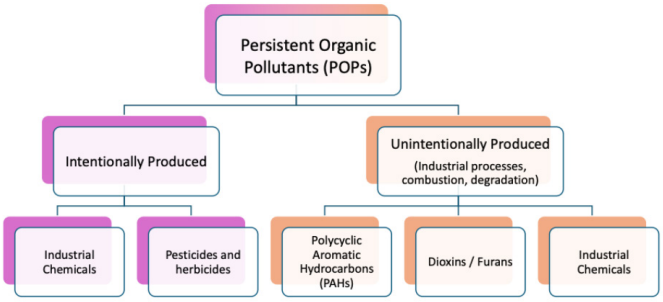
Introduction

Many chemicals have been produced to improve human lives. These chemicals are discharged and emitted into the environment and continue to be one of the main stressors on marine ecosystems.

POPs, which are generally hydrocarbons that are halogenated (containing fluorine, chlorine or bromine) (Guo and others, 2019), may be produced intentionally or unintentionally (see figure II). They include PCBs (209 individual congeners), polybrominated diphenyl ethers (PBDEs) and PFAS (see table 1). Although the manufacture of some POPs is now banned, such bans entered into effect only after significant quantities had been manufactured and used. For example, 8,896 kilotons of hexachlorocyclohexanes (HCHs) were manufactured before being banned (Li and others, 2023).

Figure II

The range of persistent organic pollutants

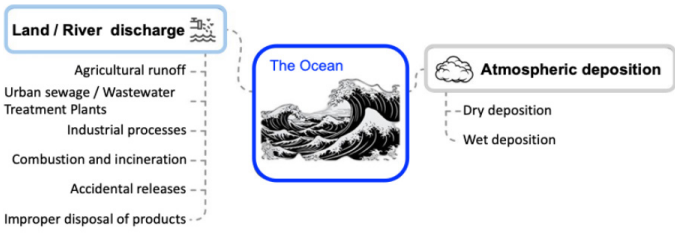


Source: Prepared by the writing team.

Note: Industrial chemicals are produced both intentionally and unintentionally. PCBs and polychlorinated naphthalenes (PCNs) are produced unintentionally during the production of paints and dyes (Hu and Hornbuckle, 2009; Hannah and others, 2022) and at nonferrous metallurgical facilities (Klimczak and others, 2023). Polychlorinated diphenyl ethers (PCDEs) are by-products of the synthesis of commercial chlorophenols (Wu and others, 2023). POPs, including PAHs, may also be produced during combustion. Although PAHs are not covered by the Stockholm Convention, they are included in the figure because they are classified as POPs.

POPs continue to be manufactured and reach the ocean through a variety of pathways (see figure III). However, these halogenated compounds persist in the environment and are bioaccumulated, especially in higher trophic levels (see figure IV). This means that as humans introduce new chemicals, further problems arise. In addition, these chemicals are dispersed by ocean currents and atmospheric winds resulting in them being found around the globe (see figure III).

Figure III
Sources of persistent organic pollutants



Source: Prepared by the writing team.

Note: Long-range atmospheric transport is primarily responsible for POPs found in the Arctic, Antarctic and other regions distant from the site of discharge. This means that POPs impact people and wildlife far from where they are released, which supports the finding in the second *World Ocean Assessment* that POPs continue to be global contaminants. Processes for removing POPs from wastewater continue to be investigated.

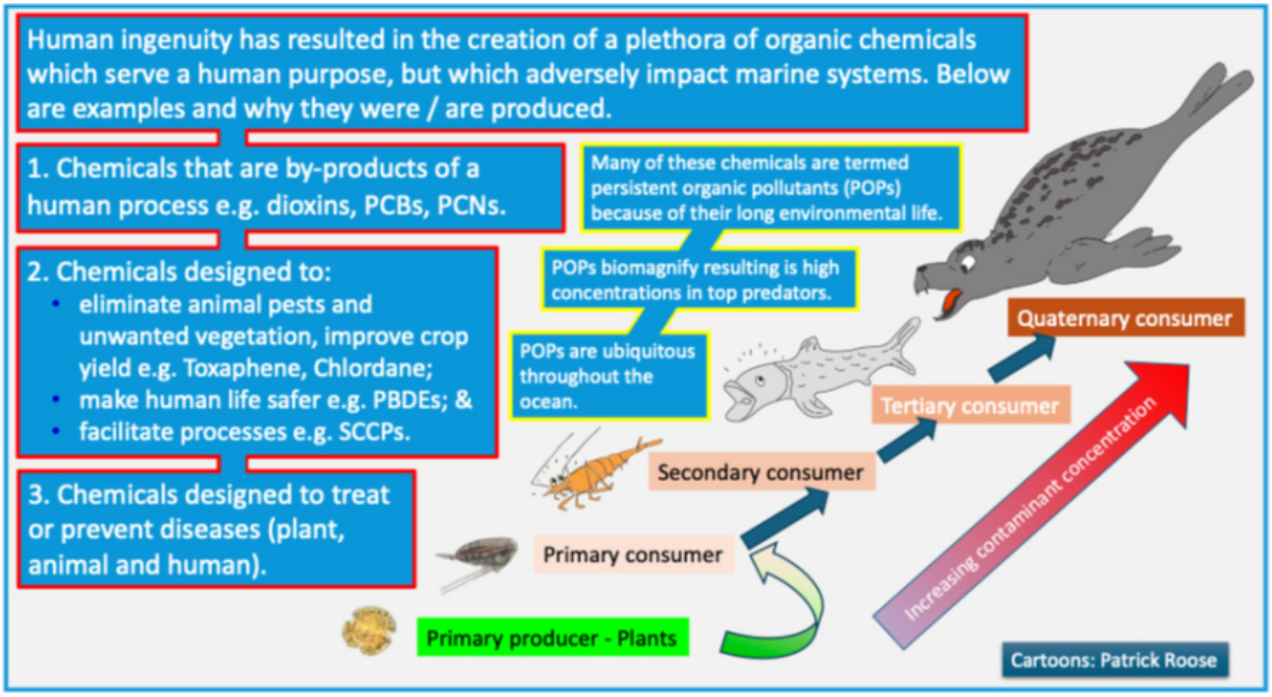
Table 1
Persistent organic pollutants

Chemical Group	Abbreviation	Chemical Group	Abbreviation
Polychlorinated biphenyls	PCBs	Per- and polyfluoroalkyl substances	PFAS
Polychlorinated diphenyl ethers	PCDEs	Perfluoroalkyl sulfonic acids	PFSAs
Polychlorinated naphthalenes	PCNs	Perfluoroalkyl carboxylic acids	PFCAs
Polybrominated diphenyl ethers	PBDEs	Organochlorinated pesticides	OCPs
Polybrominated biphenyls	PBBs	**Individual Chemical**	**Abbreviation**
Polychlorinated dibenzo-p-dioxins	PCDD	Perfluorooctanesulfonic acid	PFOS
Polychlorinated dibenzofurans	PCDF	Perfluorohexane sulfonic acid	PFHxS
Polyhalogenated carbazoles	PHCZs	Perfluorooctanoic acid	PFOA
Toxaphene	Toxaphene	Perfluoroheptanoic acid	PFHpA
Short-chain chlorinated paraffins	SCCPs	Hexachlorobenzene	HCB
Hexachlorocyclohexane	HCH	Dichlorodiphenyltrichloroethane	DDT

Source: Prepared by the writing team.

Note: PHCZs and PFHpA are not listed in the Stockholm Convention on Persistent Organic Pollutants. The Stockholm Convention lists the following groups of PFAS: PFOS, its salts and perfluorooctane sulfonyl fluoride (PFOSF) (including all PFOS precursors); PFOA, its salts and PFOA-related compounds (including all PFOA precursors); PFHxS, its salts and PFHxS-related compounds (including all PFHxS precursors); and long-chain PFCAs, their salts and related compounds (including all long-chain PFCA precursors). These groups cover many hundreds of related compounds. Organochlorinated pesticide is an umbrella term for a range of pesticides, including DDT and HCH.

Figure IV
Persistence, bioaccumulation and biomagnification of persistent organic pollutants



Source: Cartoons by Patrick Roose.

Note: These processes mean that apex predators accumulate significant concentrations of POPs. Variation in concentrations can be associated with the prey consumed. Evidence published since the publication of the second *World Ocean Assessment* has shown that there are differences in the concentration of PCBs between killer whales (*Orcinus orca*) that had a mixed diet and those that had a diet mostly composed of fish. In addition, the concentration of PCBs in male killer whales was greater than in female killer whales regardless of diet (Remili and others, 2021). Cetaceans that forage on pelagic prey species had lower contaminant loads compared with those that were benthic or coastal feeders (Remili and others, 2024).

Concentrations of persistent organic pollutants in marine ecosystems

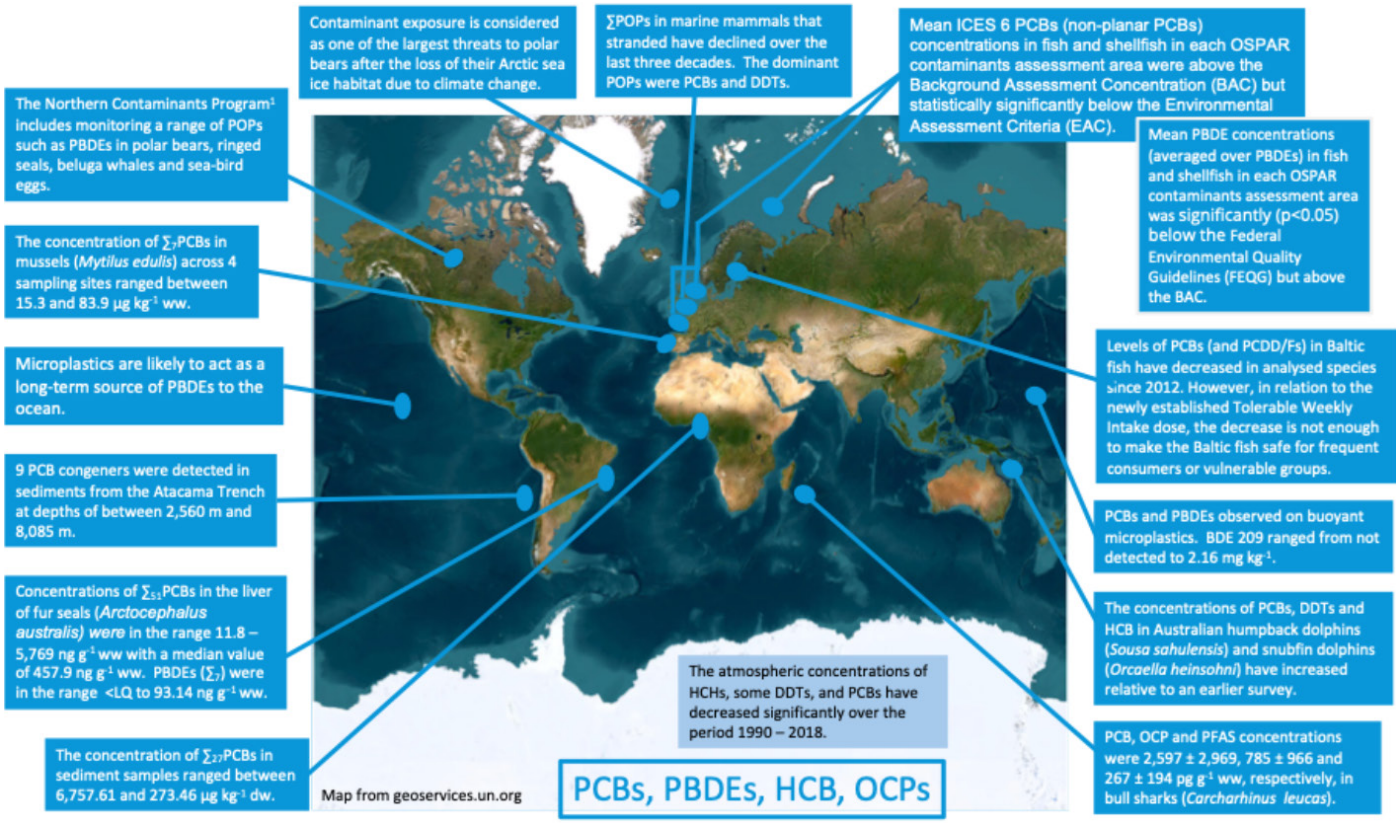
The present subchapter provides an update to the information on the concentrations of POPs in marine ecosystems contained in the second *World Ocean Assessment*.

Although the production and use of many POPs have been banned, POPs continue to be manufactured (see figure II). In the case of PCBs, for example, production has been banned for at least 30 years. In addition to legacy PCBs, there are "contemporary" PCBs that are inadvertently produced during the production of paints, dyes and other products (Hu and Hornbuckle, 2009) or during electricity production when coal is used as fuel (Montano and others, 2022; see figure II). Consequently, POPs are still present in all oceanic regions and continue to be transferred to the polar regions through atmospheric transport (see figure V(A–C)). With these compounds being detected in marine ecosystems far from their source of production or emission (see box 1), the basis of regional assessments is the determination of the concentration of POPs in water, sediment or biota. These concentrations are then assessed relative to national or international assessment criteria. Wherever samples of water sediment or biota are collected, POPs are found. Concentrations of legacy POPs are very low in some cases, but PFOA and PFOS are found globally in seawater, sediments and plankton (see figure V(C)). Time series are now long enough to enable temporal assessments for some POPs (Webster and Fryer, 2022). Replacement chemicals for listed POPs are also being detected in the ocean (Langberg and others, 2019).

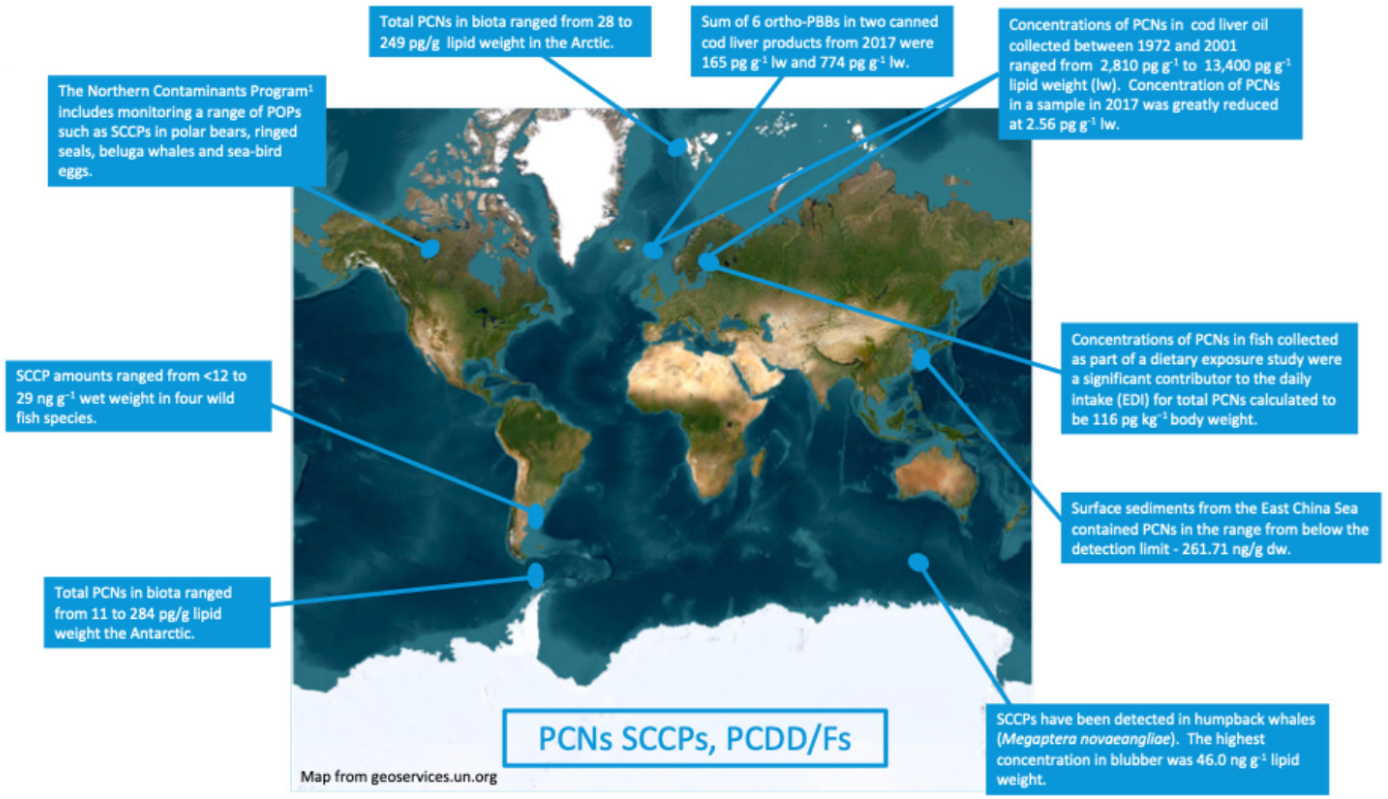
Figure V

Concentrations of persistent organic pollutants in seawater, sediments and biota, in all regions

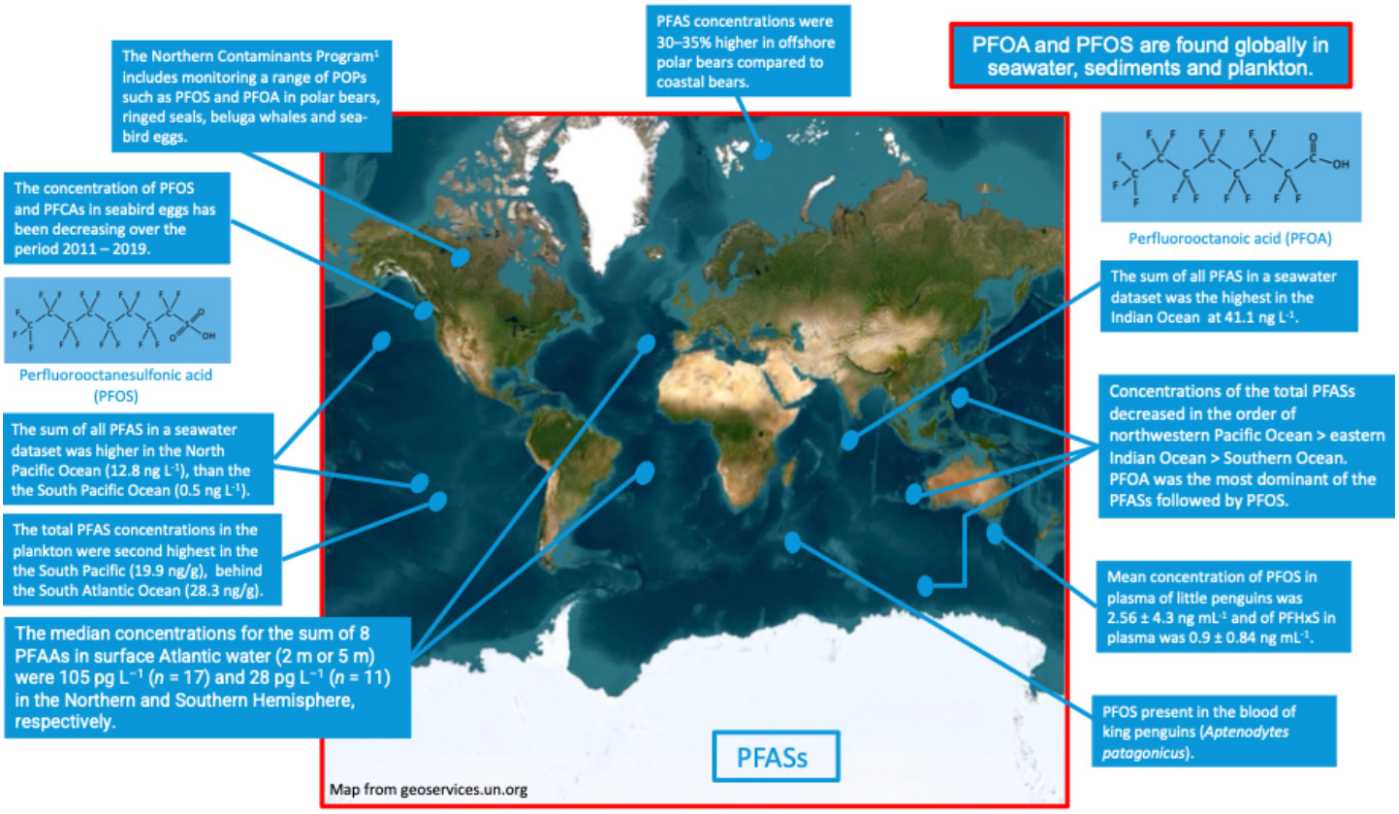
A. PCBs, PBDEs and HCB



B. PCNs, SCCPs and PCDD/Fs



C. PFAS



Sources: Prepared by the writing team based on Northern Contaminants Programme. Figure V(A): Chynel and others, 2021; Cagnazzi and others, 2020; Yeo and others, 2020; Mikolajczyk and others, 2021; Webster and Fryer, 2022; Williams and others, 2023; Routti and others, 2019; Esteves and others, 2024; Sobek and others, 2023; Turner, 2022; Pereira and others, 2024; Unyimadu and Benson, 2023; Luarte and others, 2023. Figure V(B): Casa and others, 2019; Liu and others, 2018; Zacs and others, 2021; Falandysz and Fernandes, 2020; Falandysz and others, 2020; Dong and others, 2023; Girones and others, 2023. Figure V(C): Mollier and others, 2024; Wells and others, 2024; Shan and others, 2021; Khan and others, 2023; Muir and others, 2019; Kesic and others, 2023; Savvidou and others, 2023.

Box 2

Case study: Arctic Ocean region

Overview

Persistent organic pollutants (POPs) pose a significant environmental and health threat to the ocean due to their long-term persistence, potential for bioaccumulation and ability to travel long distances (Arctic Monitoring and Assessment Programme (AMAP), 2021). One of the most affected regions is the Arctic Ocean, which acts as a primary sink for POPs transported from industrial regions through atmospheric and oceanic pathways. The cold temperatures in the Arctic slow the degradation of these chemicals, allowing them to persist in the environment for extended periods.

Changes in the overall status

Since the second *World Ocean Assessment*, the concentrations of many legacy POPs, such as polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexanes (HCHs), have generally decreased in the Arctic region. Nevertheless, this positive trend is not without exceptions. Emerging contaminants, particularly per- and polyfluoroalkyl substances (PFAS), have been increasingly detected in the Arctic. These substances, which were not previously recognized as significant threats, are now considered a growing concern due to their persistence, potential for long-range transport and bioaccumulative properties (United Nations Environment Programme (UNEP), 2019).

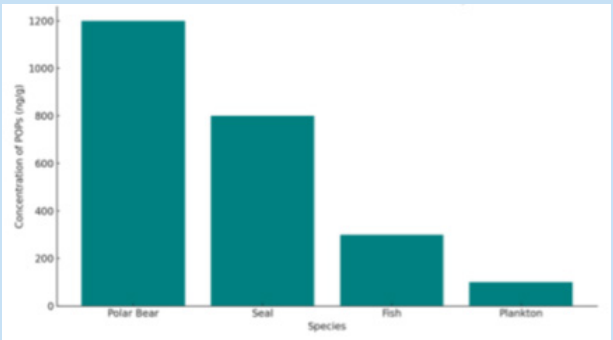
Factors contributing to the changes observed

The decline of legacy POPs in the Arctic is primarily driven by international regulations, including the Stockholm Convention; regional initiatives, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and AMAP; and a global shift in industrial practices. Reduced emissions and changes in atmospheric transport have lowered the influx of POPs to the Arctic, while environmental degradation processes and sequestration have further diminished their concentrations. As a result, POP levels have been significantly reduced, contributing to the protection of Arctic ecosystems and human health.

Impacts of the changes on, and interactions with, other components of the marine system

The changes in POP concentrations have significant implications for the Arctic marine ecosystem. POPs are known to be bioaccumulated in the Arctic food web, leading to high concentrations in apex predators, such as polar bears and seals, and there are detectable concentrations in fish and plankton (AMAP, 2021). This bioaccumulation disrupts the natural balance of the ecosystem, affecting the health and reproductive success of wildlife. Moreover, the remobilization of POPs due to climate change increases the risk of contamination in previously pristine areas, exacerbating the stress on already vulnerable species (Noyes and others, 2025). The figure illustrates the bioaccumulation of POPs in different Arctic marine species, with a focus on apex predators. The data highlight particularly high concentrations of POPs in polar bears and seals, which pose significant health risks to these species and the ecosystems they inhabit.

Figure
Bioaccumulation of persistent organic pollutants in Arctic marine species



Source: AMAP, 2021.

Social, economic and cultural aspects associated with the change

The social, economic and cultural implications of POP contamination in the Arctic are profound, particularly for Indigenous communities, which rely heavily on marine resources for subsistence, cultural practices and economic activities. Contamination of key food sources, such as seals and fish, poses serious health risks, including increased cancer rates, endocrine disruption and reproductive issues (World Health Organization (WHO), 2018). Biodiversity loss and degradation of the marine environment threaten the cultural identity and traditional practices of Indigenous Peoples, who have coexisted with the Arctic environment for millenniums (Downie and Fenge, 2003). The economic impacts are significant, as the degradation of marine resources can affect the livelihoods of those who depend on fisheries and ecotourism. The long-term sustainability of such economic activities is at risk if POP contamination continues to undermine the health of the marine ecosystem.

Implications for achieving the targets of Sustainable Development Goal 14

The observed decline in POPs in the Arctic supports the achievement of several Sustainable Development Goals, particularly those related to environmental health, clean water and the protection of life below water and on land. Continued monitoring and policy enforcement are essential to maintain and further these gains, ensuring a safer and healthier environment for both human and ecological communities in the Arctic. Nevertheless, emerging contaminants (PFAS and hexachlorobenzene (HCB)) are becoming increasingly prevalent and might pose a major challenge to protecting the marine biodiversity of the Arctic. Climate change further complicates efforts to achieve the Goals because it alters the dynamics of POP distribution, transport pathways, sources and sinks, and increases the risk of contamination in previously unaffected areas (UNEP, 2019).

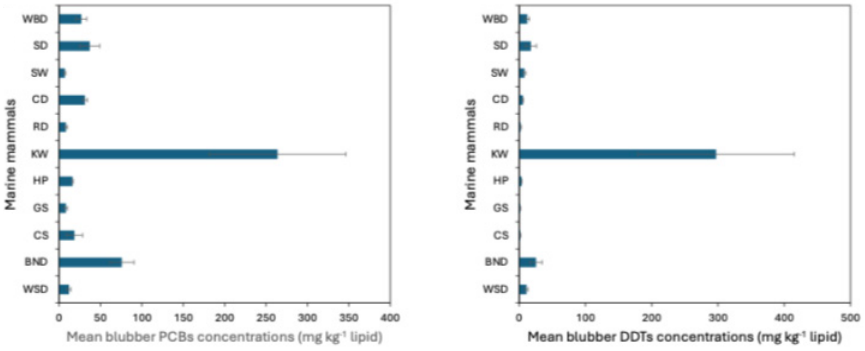
Achieving Sustainable Development Goal 14 requires a multifaceted approach, including strengthening international cooperation, enhancing regulatory frameworks and implementing targeted strategies to mitigate the impacts of POPs in the Arctic. The knowledge and perspectives of Indigenous communities must be integrated into such efforts to ensure that their cultural and socioeconomic needs are addressed in the pursuit of sustainable development.

Concentrations of POPs, including PCBs, DDT isomers, PBDEs, HCHs, HCB and dieldrin, in cetaceans are significant (see figure VI (A–C)); Williams and others, 2023). Data from cetacean strandings around Great Britain, however, show significant spatial and taxonomic heterogeneity and also reveal that the summed concentration of POPs, which was dominated by PCBs and DDTs, has declined for all species over the past 30 years. However, pollutants remain a threat to biodiversity in several species and regions covered in the study conducted by Williams and others (2023).

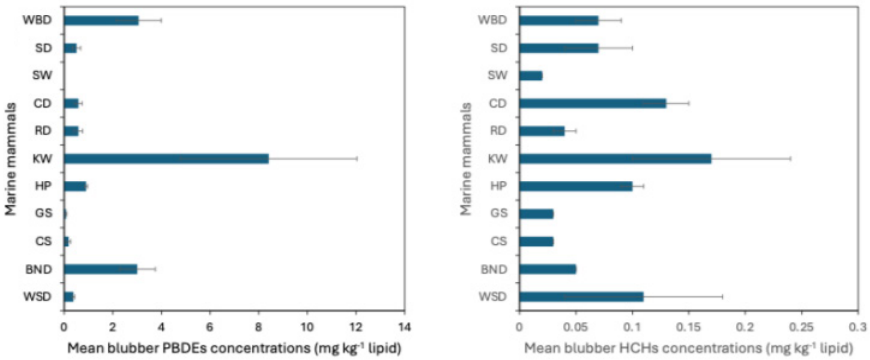
Figure VI

Mean concentration of persistent organic pollutants in the blubber of cetaceans

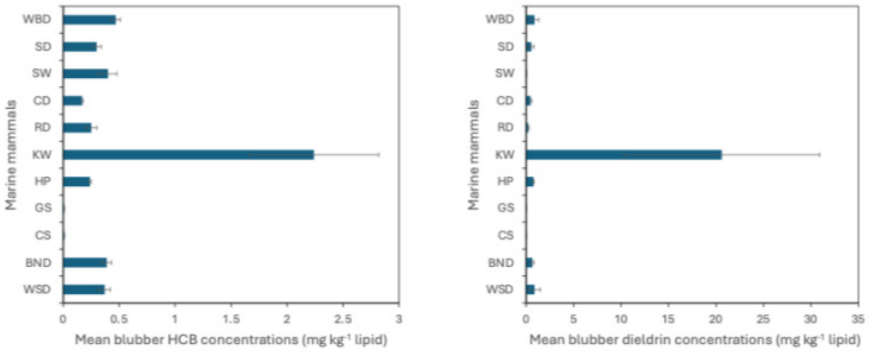
A. PCBs and DDT isomers



B. PBDEs and HCHs



C. HCB and dieldrin



Source: Produced by the authors using data from Williams and others, 2023.

Note: Mean concentration in the blubber of 11 species of cetacean that had stranded on the coast of Great Britain over the period 1990–2018 with a decomposition code of less than four. The sample size for each individual species ranged from 6 (sperm whale) to 731 (harbour porpoise). Error bars reflect standard error.

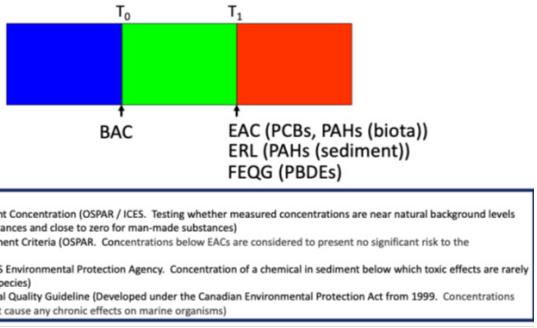
Abbreviations: BND, common bottlenose dolphin (*Tursiops truncatus*); CD, short-beaked common dolphin (*Delphinus delphis*); CS, common seal (*Phoca vitulina*); GS, the grey seal (*Halichoerus grypus*); HP, harbour porpoise (*Phocoena phocoena);* KW, killer whale (*Orcinus orca*); RD, Risso's dolphin (*Grampus griseus*); SD, striped dolphin (*Stenella coeruleoalba*); SW, sperm whale (*Physeter macrocephalus*); WBD, white-beaked dolphin (*Lagenorhynchus albirostris*); WSD, Atlantic white-sided dolphin (*Lagenorhynchus acutus*).

Use of assessment criteria

In recent years, assessment criteria have been increasingly used to determine the status of marine waters with respect to the concentration of hazardous substances, as exemplified by a recent assessment of hazardous substances in the North-East Atlantic (OSPAR, 2023). In that assessment, measured concentrations were classified into three categories: near natural background levels (for naturally occurring substances) or close to zero (for man-made substances); at or above the background assessment concentration but statistically significantly below the environmental assessment criteria or an alternative criterion selected for a given contaminant; or statistically significantly above environmental assessment criteria or the alternative (see figure VII). The results of the assessment give a clear indication of the status of marine biota, showing that although the concentrations of non-planar PCBs in fish and shellfish were all below the environmental assessment criteria in all areas assessed, concentrations of CB118 (a dioxin-like PCB) in biota were above the environmental assessment criteria in 7 of the 13 assessment areas, which indicates possible adverse effects on marine life in those areas (see figure VIII).

Figure VII

Range of assessment criteria used by the OSPAR Commission

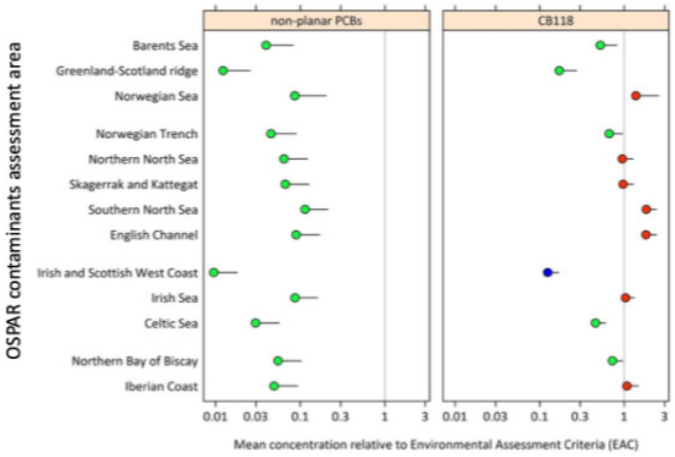


Source: Prepared by the writing team.

Note: A range of assessment criteria is used to assess the impacts of pollutants, including POPs. In this example, a blue status indicates that the concentration of the contaminant is statistically significantly below the background assessment concentration. The background assessment concentration is represented by the transition point T_0. T_1 represents the transition point between the concentration of a contaminant being at or above the background assessment concentration but statistically significantly below the environmental assessment criteria, on the one hand, and the concentration being statistically significantly above the environmental assessment criteria, on the other.

Figure VIII

Polychlorinated biphenyls in fish and shellfish, by OSPAR assessment area



Blue = statistically significantly below the BAC
Green = at or above the BAC but statistically significantly below the EAC
Red = statistically significantly above the EAC

Sources: OSPAR, 2023; Webster and Fryer, 2022.

Note: This is based on the mean concentrations of PCBs (ICES-6 PCBs (non-planar PCBs) and CB118) in fish and shellfish in each OSPAR assessment area, relative to the environmental assessment criteria (with 95% upper confidence limits) where the environmental assessment criteria value is 1. Concentrations are statistically significantly below the environmental assessment criteria if the upper confidence limit is below 1. The concentrations of the non-planar PCBs were all below the environmental assessment criteria. Concentrations of CB118 in biota exceeded the environmental assessment criteria in 7 of the 13 assessment areas, which indicates possible adverse effects on marine life in those areas. The only area where the mean concentrations of CB118 in biota were below the background assessment concentration was the Irish and Scottish West Coast.

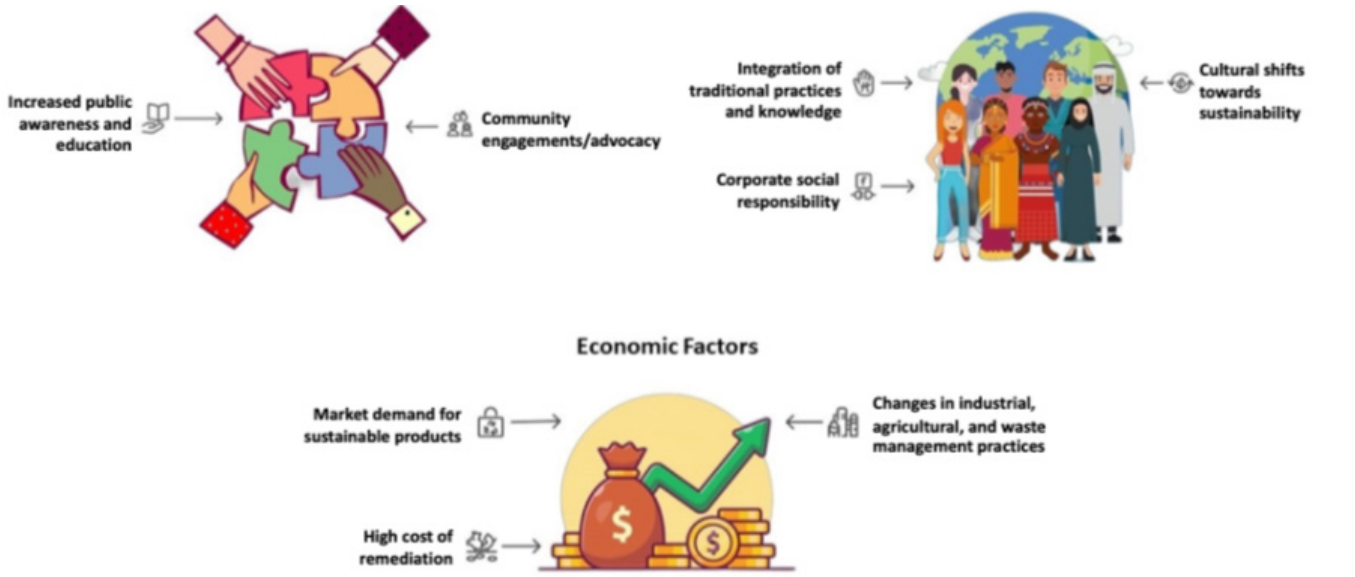
Drivers of the evolving societal response to persistent organic pollutants

The listing of POPs under the Stockholm Convention continues, which means that society is responding to the continuing problem of POPs and their impact on the environment. A combination of social, cultural and economic factors contribute to this societal response, and ultimately to a decline of concentrations of some POPs (see figure IX). For example, there is increased public awareness of the impacts of pollution on not only the ocean, but also human health. There is also growing recognition that the ocean is vitally important as part of the living system of the Earth and central to building a healthy economy and a vibrant society. This recognition, together with the implementation of measures aimed at achieving the Sustainable Development Goals (as discussed below), has helped to engender a response from communities. Improved

understanding by the scientific community and the wider public of the traditional practices and knowledge of Indigenous Peoples has also increased the awareness of environmental change due to human activities and raised the desire of people to reduce pollution. Lastly, changes in industrial, agricultural and waste management practices, owing in part to legislation but also to public demand for sustainable products, have helped.

Figure IX

Potential drivers of the decline in concentrations of some persistent organic pollutants



Source: Prepared by the writing team.

Note: Evidence points to an overall decline in the concentrations of at least some POPs. The potential reasons for that decline are multifactorial and include social, cultural and economic factors.

Ramifications for the Sustainable Development Goals

POPs are ubiquitous contaminants. Owing to the significant number of compounds and their varying half-lives, in 2025, the date set for Sustainable Development Goal target 14.1 (see figure X(A)), concentrations of certain POPs will likely be shown, through ongoing monitoring programmes, to have been greater than the levels expected to cause biological effects. More important than the levels, however, is the impact on biota generated by the multitude of POPs to which the biota are exposed, which remains difficult to assess. POPs also continue to be of concern from a human health perspective, and thus have ramifications for target 3.9 (see figure X(B)) and other Sustainable Development Goals targets (see figure X(C–E)).

Ecotoxicology

When assessing the impacts of POPs on marine ecosystems, results are often presented by individual congener or by group of congeners. For example, an assessment might focus on a dioxin-like PCB, such as CB118, or on the ICES-6 PCBs (non-planar PCBs) (Webster and Fryer, 2022). Biota, however, are not exposed to one single congener or to one single group of congeners; they are exposed to all bioavailable pollutants in their geography. For this reason, ecotoxicological assessments are vital, because some ecotoxicological tests more correctly assess the impact of all anthropogenic chemicals in the environment rather than the impact of a single compound or group of compounds.

The understanding of the concentrations and impacts of POPs in the marine environment lags behind the understanding of their concentrations and impacts in freshwater systems because fewer marine-based ecotoxicity testing models and systems exist. Testing programmes, including the chemical monitoring programmes undertaken by such agencies as the Food Standards Agency of the United Kingdom, are focused on bioaccumulative compounds within high trophic species destined for human consumption. Data on other compounds, mixtures and congeners in the marine environment are therefore limited (Hutchinson, 2017; Tlili and Mouneyrac, 2021). Of increasing concern is the impact of mixtures of chemical compounds and the combined toxicity of environmentally realistic co-occurring contaminants

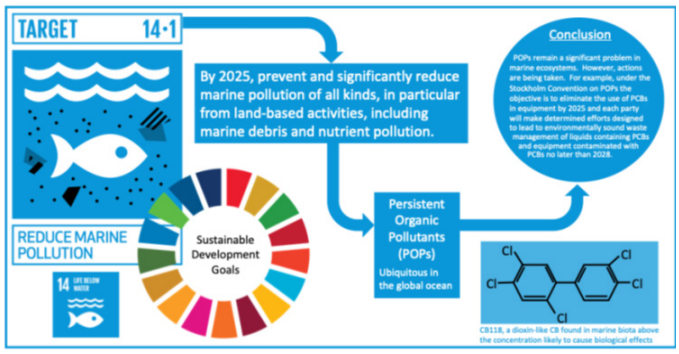
with a dynamic exposure complexity, which is difficult to replicate in laboratory toxicity testing (Burgeot and others, 2023). Chemical contaminants can interact in multiple ways, and, according to one study, synergy occurs in 7% of binary pesticide mixtures (Cedergreen, 2014). Synergistic impacts are particularly concerning due to the potential for extreme impacts not predictable by single compound toxicity testing for regulatory purposes (Orr and others, 2024; Pirotta and others, 2022). To more accurately estimate the contribution of POPs to marine multi-stressor environments, combined toxicity estimations of mixtures are urgently needed, and profiles of how climate change is altering physical stressor conditions in the marine environment need to be taken into account.

Ongoing regulatory developments continue to bring change

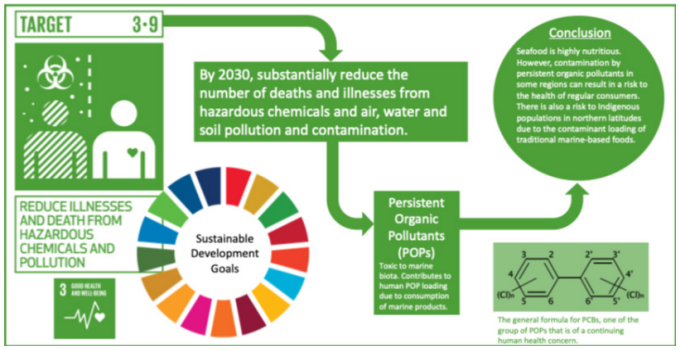
As noted, the Stockholm Convention on Persistent Organic Pollutants serves as the basis for the global regulation of POPs. Table 2 contains a description of recent developments with respect to listed chemicals and selected targets for improving management of PCBs.

Figure X
Ramifications for selected Sustainable Development Goal targets

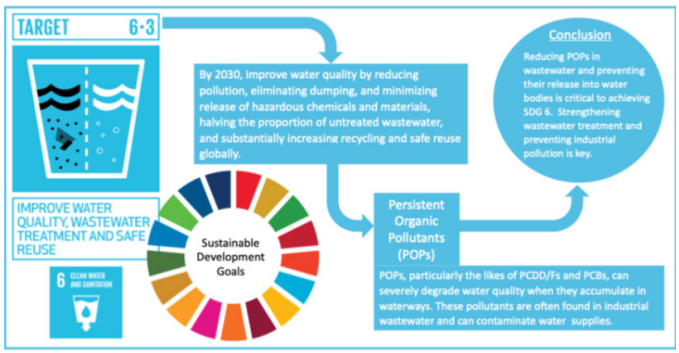
A. Target 14.1, Reduce marine pollution



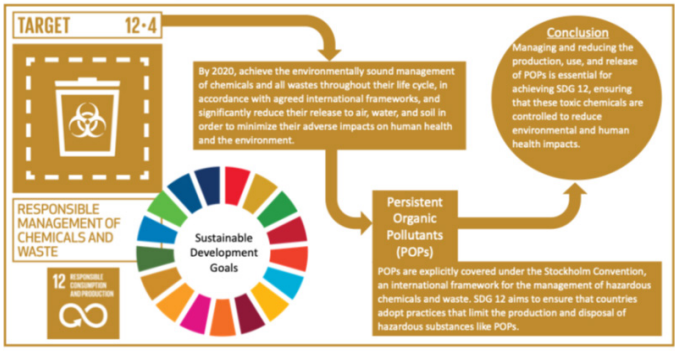
B. Target 3.9, Reduce illnesses and death from hazardous chemicals and pollution



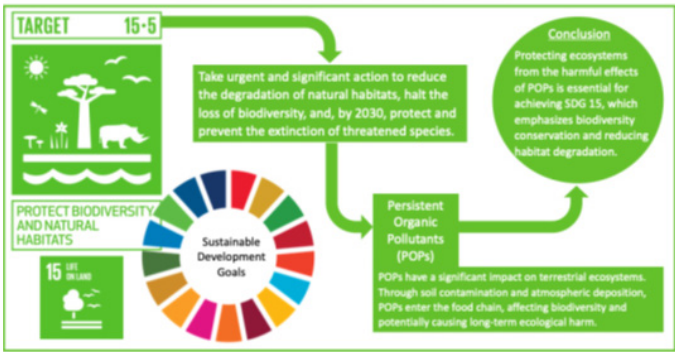
C. Target 6.3, Improve water quality, wastewater treatment and safe reuse



D. Target 12.4, Responsible management of chemicals and waste



E. Target 15.5, Protect biodiversity and natural habitats



Source: Prepared by the writing team.

Table 2
Recent regulatory developments and selected targets

Year	Decision / Change	Source
2019	The Conference of the Parties listed PFOA, its salts and PFOA-related compounds and dicofol in Annex A to the Stockholm Convention (decision SC-9/12). The Conference of the Parties also amended Annex B to eliminate many of the exemptions for PFOS, its salts and PFOSF.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2021	The regulation was revised to include stricter limits on certain POPs, such as Perfluorohexane sulfonic acid (PFHxS), which is widely used in industrial processes and can cause significant environmental harm.	European Union (2019). Regulation (EU) 2019/1021 of the European Parliament and of the Council on Persistent Organic Pollutants.
2022	The Basel Convention's COP adopted new guidelines that address the management of waste containing newly listed POPs, such as certain brominated flame retardants, and improve waste disposal practices to minimize environmental contamination.	Basel Convention Secretariat (2022). Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. United Nations Environment Programme.
2022	The Conference of the Parties listed PFHxS, its salts and PFHxS-related compounds in Annex A to the Stockholm Convention (decision SC-10/13).	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2023	The Conference of the Parties listed Dechlorane Plus and UV-328 and methoxychlor in Annex A to the Stockholm Convention.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2025	Eliminate the use of PCBs in existing equipment.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2025	The Conference of the Parties listed MCCPs, long-chain PFCAs, their salts and related compounds, and chlorpyrifos in Annex A to the Stockholm Convention.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2028	Ensure environmentally sound waste management of PCBs.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2030	Exemptions for recycling of articles containing commercial pentaBDE and commercial octaBDE expire.	The Stockholm Convention on Persistent Organic Pollutants (POPs).

Source: Prepared by the writing team.
Abbreviations: COP, Conference of the Parties; MCCPs, medium-chain chlorinated paraffins.

Key remaining knowledge and capacity gaps and new gaps

Determining the impact of the chemical mixtures to which marine organisms are exposed continues to be a key challenge. This challenge is exacerbated by the impacts of other forms of pollution, including synergistic interactions with nanoplastics (Kamalakannan and others, 2024) and the impacts of changing temperatures, water oxygen concentration and acidity driven by increasing concentrations of greenhouse gases. Analytical challenges are significant because of the complexity of POP mixtures coupled with the analytical methods required for quantification of POPs in the ocean. Lastly, human ingenuity continues to result in emerging contaminants and POP replacements, including PHCZs (Gao and others, 2024). PHCZs have been detected in marine sediments, seawater, zooplankton, bivalves, fish, harbour seals and cormorant eggs (Wu and others, 2017; Hu and others, 2021; Hu and others, 2024). Recent studies have shown that 6:2 fluorotelomer sulfonate (6:2 FTS), which has been used as an alternative for legacy PFAS, may be immunotoxic (Grimberg and others, 2024; Bohannon and others, 2023). POP replacements are often not benign, which adds further complexity to the challenge of developing an understanding of the full impact and consequences of POPs in the ocean.

4. Pharmaceuticals and personal care products

Key points

- Advances in analytical techniques have significantly enhanced the identification and quantification of PPCPs in marine environments, leading to more comprehensive data collection.
- Expanded monitoring programmes have led to a greater understanding of the prevalence of PPCPs in various oceanic regions, particularly in the North Pacific and North Atlantic.
- Studies have identified certain hotspots for the accumulation of PPCPs in coastal seas and have elucidated the effects of PPCPs on marine organisms, including such issues as bioaccumulation and toxicity to phytoplankton, fish and benthic species.
- Improvements to wastewater treatment technologies and adequate funding for the operation and maintenance of wastewater treatment facilities are necessary to reduce PPCP levels in effluents, thereby alleviating the pressure on coastal marine environments.

- Action plans and priorities have been developed on how to decrease the presence and potential impacts of pharmaceuticals in the environment. Strategies include reducing demand for and use of pharmaceuticals, improving disposal and reducing end-of-pipe emissions. The last and most expensive option is advanced wastewater treatment to remove active pharmaceutical ingredients (APIs) before their wider distribution in the environment (Caban and Stepnowski, 2021).

Introduction

PPCPs comprise a diverse array of substances, including prescription and therapeutic drugs, veterinary medications, fragrances, sunscreen agents and diagnostic compounds. At present, around 4,000 pharmaceutically active substances are available globally, and approximately 100,000 tons are consumed each year (Pawłowska and Biczak, 2024). PPCPs have increasingly generated significant environmental concern due to their persistence, bioaccumulative properties, toxic potential and, in many cases, high mobility (Chakraborty and others, 2023). Over the past few decades, many research and monitoring initiatives have employed advanced sampling and analytical techniques, such as liquid chromatography-mass spectroscopy, gas chromatography-mass spectrometry and non-targeted high-resolution mass spectrometry, to detect various PPCPs in the global ocean (Guo and others, 2023b). Commonly detected compounds include antibiotics, hormones and ultraviolet light (UV) filters, with concentrations of these substances varying across different regions.

The coronavirus disease (COVID-19) pandemic has further exacerbated this issue by significantly increasing the use of specific medications and treatments, notably antivirals, antimicrobials and antidepressants (Li and others, 2023). Mass consumption of some of these pharmaceuticals has led to a greater concentration of pharmaceutical residues in aquatic environments and river discharges. PPCPs are now pervasive in both the open-ocean and coastal areas, with particularly high concentrations found near densely populated and industrial zones, wastewater discharge points, harbours and mariculture facilities (Li and others, 2024). These pollutants can be transported through river outflows, ocean currents and atmospheric deposition, often accumulating in marine organisms and sediments, especially in marginal seas (Maghsodian and others, 2022).

The ecological impacts of PPCPs are profound and concerning. Toxicity studies have shown harmful effects on marine organisms, including endocrine disruption, the development of antibiotic resistance and behavioural changes in various marine biota, including fish, invertebrates and algae (Yang and others, 2020; Mezzelani and Regoli, 2022). The widespread presence of PPCPs poses a threat to marine biodiversity and ecosystem health. Moreover, human exposure to PPCPs, though less direct, remains a critical issue. This exposure primarily occurs through the consumption of seafood and participation in leisure activities in contaminated waters (National Academies of Science, Engineering and Medicine, 2024). Such exposure raises serious concerns about chronic health risks, including hormonal disruptions and the proliferation of antibiotic-resistant bacteria.

This assessment of PPCPs is focused on data and research published from 2018 to 2024. For information on PPCPs in the global ocean prior to 2018, see chapter 11 of the second *World Ocean Assessment*.

Environmental change since the second *World Ocean Assessment*

Recently, scientists have turned their attention to emerging chemical contaminants present in low concentrations, such as PPCPs, which pose significant threats to coastal and ocean environments through bioaccumulation and metabolism. Research and monitoring of the presence of PPCPs in marine waters is important, but there is a particular need to include metabolites in such efforts, as these compounds often go undetected and can be as persistent and hazardous as their parent substances. Table 3 shows the reported concentrations of PPCPs frequently detected in coastal waters around the world, including antibiotics, beta blockers, anti-ulcer agents, anti-epileptics, anti-asthma drugs, antihistamines, calcium channel blockers, lipid-regulating agent and hormones.

The variability of PPCP distribution is illustrated in figure XI, which shows the global distribution of six antibiotics in oceanic waters. High concentrations of antibiotics are concentrated near densely populated and industrialized coastal regions, particularly around Europe and East Asia. Moderate to high levels are also observed off southern Africa. In contrast, most open-ocean areas show low concentrations. Lower levels are evident in more remote regions, such as in the southern hemisphere and in polar areas.

Table 3
Pharmaceuticals and personal care products measured in coastal waters (ng/L)

(a)

Location	Antibiotics									
	Erythromycin		Clarithromycin		Roxithromycin		Sulfamethoxazole		Sulfamethazine	
	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024
Baltic Sea	n.d.–0.14	n.a.	0.03–14	n.a.	n.d.–0.48	n.a.	0.74–21	n.a.	n.d.	n.a.
North Sea	0.13–0.94	n.a.	0.4–1.66	n.a.	n.d–2.86	n.a.	1.78–13.0	n.a.	n.d.	n.a.
Aegean Sea	n.d.	n.a.	16	n.a.	n.a.	n.a.	3.8	n.a.	n.a.	n.a.
Adriatic Sea	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.02–1.02	n.a.	n.a.	n.a.
Mediterranean Sea	9	n.d.–2.3	5	n.d.–441.4	n.a.	n.d.–1.3	14	n.d.–99	n.a.	n.d.–9.1
Pearl River Delta (China)	n.d.–126	n.a.	n.a.	n.a.	n.d.–12.0	n.a.	n.d.–40.6	n.a.	n.a.	n.a.
Bohai Sea	n.a.	0–150	n.a.	0.82–37	n.a.	0–630	n.a.	0–140	n.a.	0–130
Yellow Sea	n.a.	0–121.2	n.a.	0–6.55	n.a.	0–11.8	n.a.	0–1.92	n.a.	0–250.66
East China Sea	n.a.	0–57.07	n.a.	0–6.38	n.a.	0.33–34.81	n.a.	0.81–16.65	n.a.	0–2.03
South China Sea	n.a.	0–1900	n.a.	0.06–1.5	n.a.	0–47	n.a.	0–17.5	n.a.	0–16.4
Boulder basin (United States)	<1.0	n.a.	n.a.	n.a.	n.a.	n.a.	5.4 ± 11	n.a.	n.a.	n.a.

(b)

Location	ICM X-ray				NSAIDs				Anti-epileptic	
	Iomeprol		Iopromide		Diclofenac		Ibuprofen		Carbamazepine	
	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024
Arctic, Longyearbyen (Norway)	n.a.	n.a.	n.a.	n.a.	1–4	n.a.	0.4–1	n.a.	n.a.	n.a.
Arctic, Tromsø (Norway)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.–52	n.a.	n.a.	n.a.
Baltic Sea	1.05–34.5	n.a.	0.42–3.34	n.a.	n.d.–48	n.d.–27.1	n.a.	n.d.–1219.7	1.98–10.6	0.6–12.2
North Sea	7.66–207	n.a.	7.27–34.1	n.a.	n.d.–4.82	<MQL–35.35	n.a.	47.12–209.6	4.78–29.7	<MQL–78.9
Himmerfjärden (Sweden)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.0–12.0	n.a.
Aegean Sea	83	n.a.	109	n.a.	4.6	n.a.	n.a.	n.a.	2.9	n.a.
Adriatic Sea	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.11–0.36	n.a.
Sea of Marmara (Türkiye)	n.a.	n.a.	n.a.	n.a.	n.a.	<MDL–1300	n.a.	<MDL–2130	n.a.	<MDL–1840
Mediterranean (Spain)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.–31.9	n.a.	n.a.	n.a.	n.d.–31.1
Mediterranean (Tunisia)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.–23	n.a.	n.d.	n.a.	n.d.–0.5
Mediterranean (Italy)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.–441	n.a.	n.d.–2550	n.a.	n.d.–123
Gran Canaria	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.–344	n.a.	n.a.	n.a.	n.a.
Tejo estuary (Portugal)	n.a.	n.a.	n.a.	n.a.	n.a.	1.6–51.8	n.a.	<LOQ	n.a.	n.d.
Bay of All Saints (Brazil)	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	326.1–2094	n.a.	n.a.	n.a.
Guaruja (Brazil)	n.a.	n.a.	n.a.	n.a.	n.a.	85.7	n.a.	n.a.	n.a.	0.1
Sao Paulo coast (Brazil)	n.a.	n.a.	n.a.	n.a.	n.a.	9.9	n.a.	n.a.	n.a.	0.5
Santa Catarina (Brazil)	n.a.	n.a.	n.a.	n.a.	n.a.	7.9	n.a.	n.a.	n.a.	0.3
Red Sea	n.a.	n.a.	n.a.	n.a.	14020	n.d.–26.9	508	n.a.	110	n.a.
Klang River estuary (Malaysia)	n.a.	n.a.	n.a.	n.a.	n.a.	0.47–10.8	n.a.	n.a.	n.a.	n.a.
Durban (South Africa)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	170	n.a.	n.a.
Bohai and Yellow Sea	n.a.	n.a.	n.a.	n.a.	n.a.	<MDL–1.53	<MDL–5.11	<MDL–5.11	n.a.	n.d.–38.26
Boulder Basin (United States)	n.a.	n.a.	n.a.	n.a.	<1.0	n.a.	n.a.	n.a.	3.9 ± 5	n.a.
Sydney estuary (Australia)	n.a.	n.a.	3–12.5	<0.1–94.3	n.a.	n.a.	n.a.	<0.5	n.d.–2.7	<0.1–106.4

Table 3 (*continued*)

(c)

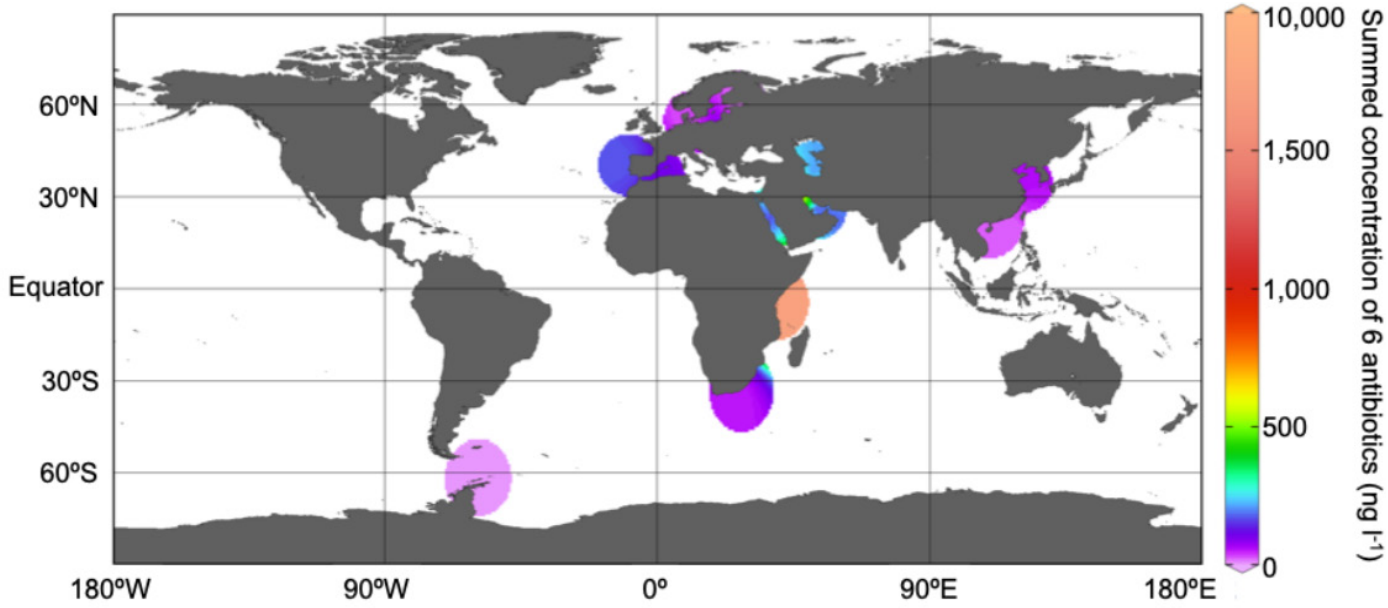
Location	Lipid regulation (ng/L)	Beta blockers (ng/L)			Antidepressants (ng/L)	
	Bezafibrate	Atenolol	Metoprolol	Propranolol	Fluoxetine	Citalopram
Baltic Sea	n.d.–0.64	n.a.	0.1–0.8	n.a.	n.a.	n.a.
North Sea	n.d.–2.06	<MQL–30.8	<MQL–23.5	<MQL–35.2	<MQL	<MQL–23.3
Aegean Sea	3.5	n.a.	n.a.	n.a.	n.a.	n.a.
Adriatic Sea	0.02–0.14	n.a.	n.a.	n.a.	n.a.	n.a.
Mediterranean (Spain)	n.d.–0.5	0.4–138.9	n.d.–5.1	n.d.–5.9	n.d.–0.6	n.a.
Mediterranean (Tunisia)	n.d.	n.d.	n.d.	n.d.	n.d.–41	n.a.
Mediterranean (Italy)	n.d.	0.1–451	n.a.	n.a.	n.a.	n.a.
Tejo estuary (Portugal)	0.84–13.4	0.49	n.a.	0.02–1.89	1.09–16.2	n.a.
Atlantic (Rías Baixas, Spain)	n.a.	n.a.	n.a.	n.a.	n.d.–10.6	n.d.–92.5
Guaruja (Brazil)	n.a.	0.3	n.a.	n.a.	n.a.	n.a.
Sao Paulo coast (Brazil)	n.a.	13.2	n.a.	n.a.	n.a.	n.a.
Santa Catarina (Brazil)	n.a.	3.2	n.a.	n.a.	n.a.	n.a.
Bohai and Yellow Seas	n.d.–3.55	n.d.–4.35	n.d.–0.46	n.d.–1.43	n.a.	n.a.
Puget Sound (United States)	n.a.	n.a.	1.5	n.a.	n.a.	n.a.
Sydney estuary (Australia)	n.a.	n.a.	<0.05–7.7	n.a.	<0.1–36	<0.1–2.6

Source: Prepared by the writing team.

Abbreviations: ICM, iodinated contrast medium; LOQ, limit of quantification; MDL, method detection limit; MQL, method quantification limit; n.a., not available; n.d., not detected; ng/L, nanograms per litre; NSAIDs, non-steroidal anti-inflammatory drugs.

Figure XI

Geographical distribution of selected antibiotics in the world's oceans



Source: Prepared by Zhiyong Xie, using Ocean Data View.

Note: The six antibiotics included are azithromycin, enrofloxacin, florfenicol, ofloxacin, sulfamethoxazole and trimethoprim.

A global monitoring study of pharmaceuticals in rivers, published in 2022, highlighted the potential transport of these compounds from river systems to the world's seas and oceans. The most contaminated samples reported were from rivers in Africa and Asia. As many as 53 APIs were detected at a single sampling site, and four APIs were detected in sampling sites on all continents: caffeine, nicotine, acetaminophen/paracetamol and cotinine (Wilkinson and others, 2022).

Region-specific changes

Arctic Ocean

PPCP residues have been detected in various environmental compartments, from coastal seawater to high-level biota, in the Arctic. The primary sources of these pollutants are local, domestic and municipal wastes, along with sewage. The lack of modern wastewater treatment plants in larger Arctic settlements results in higher PPCP release rates into the Arctic aquatic environment. By 2018, 110 PPCP-related substances had been found in the Arctic, with detectable residue concentrations. In the European Arctic, 11 pharmaceutical substances were measured in seawater and plankton samples collected in the Arctic fjord at Ny-Ålesund in 2019 (Korkmaz and others, 2022). 17-alpha-ethynylestradiol and fenoprofen were the most frequently detected pharmaceuticals, ranging from 340 to 850 nanograms per litre (ng/L) and 230 to 600 ng/L, respectively. These levels were higher than those of estrone (ranging from less than 43 to 420 ng/L) and 17-beta-estradiol (ranging from less than 29 to 140 ng/L), with the estrone detected likely being primarily a degradation product of 17-beta-estradiol. The diclofenac, ibuprofen and naproxen concentrations determined by Korkmaz and others (2022) were also higher than those found in other studies of the Arctic. Choi and others (2020) measured PPCPs in effluent and seawater collected at Ny-Ålesund using the target, suspect and non-target screening methods. PPCPs, including caffeine, paraxanthine, theophylline, acetaminophen, cetirizine, diethyl toluamide (DEET) and icaridin, were detected in all samples, with concentrations ranging from 4 to 280,000 ng/L in effluents and from 2 to 98 ng/L in seawater. In the Canadian Arctic, organic diffusive gradients in thin film (o-DGT) passive samplers were deployed in Iqaluit and Cambridge Bay to monitor PPCPs in Nunavut (Stroski and others, 2020). Seven APIs (atenolol, carbamazepine, metoprolol, naproxen, sulfapyridine, sulfamethoxazole and trimethoprim) were found at least once, with concentrations varying from non-detectable to 5,200 ng/L. Due to the cold climate, these pharmaceuticals degrade slowly, resulting in prolonged presence. Consequently, the toxicological impact of PPCP release in the Arctic differs from that in temperate regions, posing exposure risks to local populations through contaminated fish and resistant microbes.

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Adenaya and others (2024) analysed 62 APIs and one UV filter from the surface microlayer to the corresponding underlying water (0 cm, 20 cm, 50 cm, 100 cm and 150 cm) at four stations in the southern North Sea. Eleven APIs (caffeine, carbamazepine, gemfibrozil, ibuprofen, metoprolol, salicylic acid, clarithromycin, novobiocin, clindamycin, trimethoprim and tylosin) were detected in more than 95% of all seawater samples, while benzophenone-4, the UV filter, was detected in 83%.

Since 2020, following the recommendations from HELCOM, several studies have been carried out to investigate the occurrence, transport, sedimentation and bioaccumulation of APIs in riverine run-off and the estuaries of the Baltic Sea. In the eastern Gulf of Finland, seven APIs were identified in seawater samples, including caffeine (81%), carbamazepine (81%), ketoprofen (60%), diclofenac (23%), ciprofloxacin, trimethoprim and clarithromycin, with concentrations varying from 0.1 to 4,500 ng/L. Antibiotics were found in trace amounts. In sediment samples, six APIs were detected with concentrations ranging from 0.1 to 66 ng/g (Chernova and others, 2021). Kucharski and others (2022) investigated 130 APIs in sediments collected from the Odra River estuary (south-west Baltic Sea). Of those 130 APIs, 48 were detected at concentrations above the limit of quantification in at least 10% of the sampling sites. Carbamazepine, sulpiride, fexofenadine, clindamycin, tramadol, bisoprolol and lidocaine were found to be the most frequently occurring compounds in the sediment. In most cases, levels of APIs recently measured in seawater and sediment from the Baltic Sea were in line with the levels detected in effluents from the surrounding region (Zandaryaa and Frank-Kamenetsky, 2021; Undeman and others, 2022; Jucyte-Cicine and others, 2024). Bobrowska-Korczak and others (2021) screened for 98 multi-class APIs, including cardiovascular drugs, antidepressants, antibiotics and sulfonamides, in the muscle tissue of fish caught in the Baltic Sea. Eleven pharmaceuticals (bisoprolol, carbamazepine, clarithromycin, erythromycin, fluoxetine, metronidazole, ofloxacin, promazine, sulfadimethoxine, thiabendazole

and tianeptine) were detected in fish muscle, while none of them were found in bream and crucian, two of the seven species in the study.

The Danube River is an important source of PPCPs entering the Black Sea and the Mediterranean. Alygizakis and others (2016) measured PPCPs in seawater from the north-western part of the Black Sea using non-target screening and deep learning convolutional neural networks. Thirty-five PPCPs were tentatively identified by library spectrum match (Alygizakis and others, 2022). PPCPs have been measured in seawater from the Mediterranean since 2016 (Alygizakis and others, 2016). Of the 158 APIs targeted by Alygizakis and others, 38 were detected, 15 of which had frequencies of detection equal to or higher than 50%. Amoxicillin, caffeine and salicylic acid were the compounds with the highest detected values, with concentrations ranging from less than 5.0 to 130 ng/L, from 5.2 to 78 ng/L and from less than 0.4 to 53 ng/L, respectively. Western Mediterranean coastal areas, including Mar Menor lagoon in south-east Spain and the Ebro Delta in north-east Spain, have been screened for UV filters and synthetic musks. Musks (galaxolide (HHCB) and hexylcinamal) and UV filters (homosalate, ethylhexyl salicylate, octocrylene and dibutyl adipate) were detected in samples taken in those areas in summer months, with concentrations varying from a few ng/L to thousands of ng/L (García-Pimentel and others, 2023). In Augusta Bay, southern Italy, APIs were studied simultaneously in untreated wastewater (concentrations ranging from 2,426 to 67,155 ng/L), marine receiving water (concentrations ranging from approximately 550 to 27,889 ng/L) and seawater (concentrations ranging from approximately 12 ng/L to approximately 280 ng/L). These data demonstrate a clear concentration gradient, with API levels decreasing progressively from untreated wastewater to coastal receiving waters and further into offshore seawater (Feo and others, 2020). The substances with the highest concentrations in seawater included ciprofloxacin, ofloxacin, atenolol, irbesartan, losartan, valsartan and carbamazepine. Valsartan was detected at the highest concentration in all samples, ranging from 209 to 1,057 ng/L.

South Atlantic Ocean and wider Caribbean

PPCPs have been measured in seawater, sediment and biota in Camps Bay, off the South Atlantic coast of South Africa. Diclofenac, acetaminophen and carbamazepine present in sewage entered the Bay but were diluted quickly by the upwelling current (Ojemaye and others, 2022). The concentrations of caffeine, diclofenac and carbamazepine, all in the single ng/L range, were similar to levels detected in other marine regions, while concentrations of triclosan and acetaminophen were much lower than those found in other studies. UV filters were found in seawater and lionfish samples collected in Grenada, West Indies. Oxybenzone was the most frequently detected compound, with concentrations varying from not detected to 120 ng/L in seawater and from 0.12 to 2.9 micrograms per kilogram (µg/kg) wet weight in lionfish muscle (Horricks and others, 2019).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

In the Indian Ocean, Ohoro and others (2021) studied APIs in water and sediment on the south-east coast of South Africa. Carbamazepine and trimethoprim were found in most sediment samples, with average concentrations of 8.75 ± 1.45 ng/g dry weight and 1.62 ± 0.83 ng/g dry weight, respectively. APIs were not detectable in seawater in all seasons. Ali and others (2017) found that concentrations of PPCPs in the Saudi Arabian coastal waters of the Red Sea were relatively high due to low water exchange with the open sea, ranging from 7 ng/L to greater than 3,000 ng/L for metformin, from less than the limit of quantification to 2,400 ng/L for acetaminophen and from 62 ng/L to more than 3,000 ng/L for caffeine. Daliri and others (2022) detected two antibiotics, amoxicillin and azithromycin, in urban wastewater discharged into the Persian Gulf, with concentrations of up to 335,000 ± 105,000 ng/L and 288,000 ± 38,000 ng/L, respectively, which shows that the volume of antibiotics being released into the northern Gulf is concerning. Mirzaie and others (2022) studied the concentration of azithromycin in seawater (7 ng/L) and sediment (5–10 ng/g) in the Persian Gulf in 2020 and found that levels were three to four times higher than pre-pandemic levels.

South and North Pacific Ocean

The coastal waters of the main island of Fiji in the South Pacific have been screened for pharmaceuticals. Seventy-two of 80 APIs were quantified at least once, with average concentrations ranging from 0.04 ng/L for diltiazem to 19 ng/L for ketoconazole (Dehm and others, 2021). Most studies carried out in the North Pacific have been focused on the marginal seas of China, the Republic of Korea and Japan. Nearshore areas exhibit higher PPCP levels due to direct discharge from urban wastewater and riverine inputs, with concentrations ranging from a few µg

to a few ng per litre. Commonly detected PPCPs include antibiotics, antioxidants, analgesic and anti-inflammatory drugs, caffeine and synthetic musk fragrances. In contrast, offshore waters exhibit significantly lower concentrations, typically in the low ng per litre range, due to oceanic current dilution and degradation processes (Lu and others, 2023; Guo and others, 2023a). In the Bohai Sea (Guo and others, 2023b), PPCPs were widely detected in seawater, sediments and benthic organisms, with 1H-benzotriazole, an antioxidant, emerging as the most prevalent PPCP. Along the coasts of the Bohai and Yellow Seas, the total concentrations of 30 PPCPs in Chinese coastal waters ranged from 0.88 to 1,200 ng/L, varying significantly from compound to compound but generally being higher than the concentrations of PPCPs in Korean coastal waters, which ranged from 9.9 to 440 ng/L.

Southern Ocean

Data on PPCPs in the Southern Ocean are scant due to its remoteness from the continents where PPCPs are used. Nevertheless, relatively high concentrations of PPCPs have been measured in glacial rivers and coastal seawaters near research stations. Concentrations of PPCPs in the Antarctic have been influenced mainly by the type of treatment systems used at research stations. The primary issue is the lack of tertiary treatment in most research stations, which leads to higher concentrations of PPCPs in their effluents. Wastewaters from Antarctic research stations have been found to contain 56 different PPCPs, while 23 PPCPs have been detected in nearby coastal waters and sea ice (Balakrishna and others, 2023). Concentrations of substances such as UV filters and antibiotics in wastewater are in the range of a few µg/L. In contrast, due to dilution and degradation, concentrations of the same substances in coastal waters and sea ice are two orders of magnitude lower (Emnet and others, 2015; Perfetti-Bolaño and others, 2022).

Remaining research gaps

Studies of PPCPs are predominantly focused on coastal areas that receive discharges from sewage, wastewater treatment plants and river run-off. Future research needs to be focused more on PPCPs in the open ocean and their long-range transport through ocean currents. There is also limited knowledge about the long-term ecological impacts of chronic high-level PPCP exposure on marine organisms.

Comprehensive data on global distribution of PPCPs are also lacking, especially in understudied regions, such as the South Atlantic, the Caribbean Sea, the South Pacific and the Indian Ocean. A lack of standardized methods for sampling, analysis and reporting further hinders efficient comparability for assessment and modelling.

Data on the full extent of PPCPs present in the global ocean are limited by non-validated methods and target analyte lists. Agreeing on a few PPCPs for baseline monitoring would help to fill in important data gaps.

Addressing these gaps is essential for effective mitigation of the impact of PPCPs on the global ocean, which includes expanded wastewater treatment, improved wastewater treatment technologies where treatment is already present, the provision of adequate funding for maintenance and operations, stricter regulations on the disposal and management of pharmaceuticals and enhanced public awareness about the environmental impact of PPCPs. The potential for long-term health effects necessitates further research and comprehensive risk assessments so that such risks can be better understood and mitigated. Continued research and international collaboration are essential to developing effective strategies to reduce the presence and impact of PPCPs, thereby protecting marine ecosystems and public health.



Ines Goovaerts

5. Plastic pollution

Key points

- Global plastic waste emissions are rising, with significant leakage from mismanaged waste, microplastic abrasion and loss, littering and marine activities.
- Plastics, especially microplastics, impact all marine ecosystems, with over 4,000 species affected. In some regions, there are debates on whether the impacts are significant.
- Plastic pollution costs billions of dollars annually. Addressing the issue requires reducing production, promoting reuse, rethinking product design, advancing material science innovations in recycling, controlling the full plastic life cycle and finding alternatives to single-use plastics in addition to legal bans to help to lessen the scale of the problem.
- Negotiations are currently under way to develop a legally binding treaty against plastic pollution, as called for in United Nations Environment Assembly resolution 5/14, to address the full life cycle of plastic products and additives,[1] in alignment with several Sustainable Development Goals and regional action plans from around the globe.

Introduction

Plastic pollution has been driven by the rise in production since the 1950s and the persistence of plastic in the environment (Geyer, 2020). Plastic waste emissions are estimated at 52.1 million metric tons per year; littering is the largest source in the global North, while uncollected waste is the largest source in the global South (Cottom and others, 2024).

Plastics, especially microplastics, impact all marine ecosystems (Suaria and others, 2020; Bergmann and others, 2022; Pierdomenico and others, 2023). Single-use plastics account for 40% of global litter, while fishing gear accounts for 15% (Morales-Caselles and others, 2021). Variations exist between high- and low-income countries.

Changes since the publication of the second *World Ocean Assessment*

Changes in the overall status and contributing factors

Recently, there have been advancements in the understanding of marine plastic pollution owing to more precise data from satellite-based detection and other new methods for detecting microplastics and nanoplastics (Huang and others, 2023; Cózar and others, 2024). In addition, predictive tools have been developed (Rieger and others, 2024), and there are now regional assessments with common indicators agreed and monitored through regional seas conventions, including the OSPAR *Quality Status Report 2023*, the United Nations Environment Programme *Mediterranean Quality Status Report* and the HELCOM *State of the Baltic Sea 2023: Third HELCOM Holistic Assessment 2016–2021*. River and stormwater overflows driven by extreme weather events are major contributors of riverine litter (Lebreton and others, 2017; Meijer and others, 2021; Cózar and others, 2024; Nyberg and others, 2023; Zhang and others, 2023; Kaandorp and others, 2023).

Macro- and microplastics currently floating in the oceans and microplastics on beaches each account for 3% to 4% of total ocean plastic (Isobe and Iwasaki, 2022). Estimates indicate that there are 24.4 trillion pieces of microplastics in the world's upper oceans (Isobe and others, 2021). Plastics in deep-sea and coral reef ecosystems are also well-documented (Corinaldesi and others, 2021; Galgani and others, 2022; Nakajima and others, 2021; Pinheiro and others, 2023), and concentrations of plastics in remote areas and the deep sea are increasing (Galgani and others, 2021).

Studies have also shown that microplastics have infiltrated every ocean layer, including hadal trenches (Egger and others, 2020; Zhao and others, 2022, 2023, 2025; Peng and others, 2018). Recent estimates indicate that there may be substantial microplastic concentrations in the water column, which are gradually exported to the deep ocean (Sonke and others, 2022; Harris and others, 2023).

Interactions with other components of the marine system

Plastic pollution poses a significant threat to marine habitats and natural processes, reducing ecosystem resilience, threatening human livelihoods and food security and causing harm to biota (see also subsect. 5A, subchaps. 1A, 1B and 1D on fisheries and aquaculture, chap. 4 on tourism and chap. 6 on shipping). According to the LITTERBASE online portal, 4,076 marine species are reportedly affected by litter.

[1] The fifth session of the intergovernmental negotiating committee to develop an international legally binding instrument on plastic pollution, including in the marine environment, was held from 25 November to 1 December 2024 in the Republic of Korea.

Microplastics arise from multiple sources, including tyres, textiles, cosmetics, paint and the fragmentation of larger items (Weis and others, 2022; Thompson and others, 2024), with documented impacts to the environment (Tamis and others, 2021; Leistenschneider and others, 2023). While advanced sewage and wastewater treatment plants may remove some of these particles (Liu and others, 2021), millions still enter water bodies, and most contain toxic or hormonally disruptive additives, including phthalates and dyes.

Social, economic and cultural impacts

The social and economic costs of plastic pollution are significant, with the tourism, fishing and shipping sectors losing billions of dollars annually due to reduced revenue and clean-up activities (UNEP, 2021). While efforts to collect and recycle valuable plastics exist, solutions must prioritize innovation in material science, eco-design, reuse and durable alternatives to single-use plastics and fishing gear configurations, with recycling as the final option in the waste hierarchy. There are ongoing challenges with bioplastics, which can release microplastics, oligomers and toxic chemicals with largely unknown health risks (Paul-Pont and others, 2023; Zimmermann and others, 2020). Improved waste management technologies, such as those that incorporate artificial intelligence and robotics, and public engagement in sustainable practices and recycling are essential steps forward (Fang and others, 2023).

Policy developments at the international and regional levels

A number of global initiatives are being considered at various forums, including the negotiations on an international legally binding instrument on plastic pollution, including in the marine environment, as called for in United Nations Environment Assembly resolution 5/14. The negotiations represent a crucial step towards economic and social transformation (Center for International Environmental Law (CIEL), 2022; Lampitt and others, 2023; Maes and others, 2023; Syberg and others, 2024). In addition to containing essential provisions on downstream measures, such as advancements in waste management, the treaty ideally will apply a comprehensive approach to the plastic life cycle and emphasize prevention, in alignment with Sustainable Development Goals 3, 6, 11, 14 and 15 while complementing existing governance structures (Maes and others, 2023). The UNEP Regional Seas Programme also addresses ocean degradation, fostering collaboration among 143 member States through 18 regional seas conventions. Under 14 of those conventions, there are regional plans to combat marine litter, some of which are legally binding. These efforts are complemented by national and local action plans, as well as by active involvement of non-governmental organizations (NGOs).

Region-specific changes

The understanding of various aspects of plastic pollution, including the sources and the impact on the marine environment, vary across the different ocean basins (see table 4). Most recent scientific studies have found no significant change in the amounts of marine litter worldwide, with specific areas being classified as non-good status (UNEP, 2024), except in remote areas, where increasing amounts of plastic are found (Galgani and others, 2021). Nevertheless, there is evidence that certain components of plastic pollution have been decreasing in recent years, such as microplastics in the North Sea, thanks to the implementation of management, reduction and prevention measures and good practices (Kühn and others, 2023). In addition, bans on priority single-use plastics recently adopted in some regions have led to significant reductions in beach pollution, with decreases of up to 30% in areas such as Europe, including the Mediterranean, and the United States of America (Marine Strategy Framework Directive (MSFD) Technical Group on Marine Litter, 2024; UNEP, 2024; Papp and Oremus, 2025).

Table 4
Overview of the state of knowledge of marine litter in the different basins of the world ocean

Ocean	Sources/ distribution	Importance	Circulation	Impacts
Arctic Ocean	+++	+++	+++	++
North Atlantic, Baltic Sea and North Sea	++	++	+	+
Mediterranean Sea and Black Sea	+	+	+	+
South Atlantic Ocean	+++	++	++	+++
Indian Ocean	++	+++	++	+++
North Pacific	++	+	+	+
South Pacific	++	++	++	+++
Southern Ocean	++	++	++	++

Quantities of Plastic		Limted		moderate
		significant		important

Uncertainties/ Knowledge gaps	low	significant	critical
	+	++	+++

Source: Prepared by the writing team.

Note: The Caribbean Sea is included under the heading "South Atlantic".

Knowledge and capacity gaps

UNEP, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), the Group of Seven (G7) and the Group of 20 (G20) support a comprehensive approach to assessing plastic pollution and its socioeconomic impacts, focused on monitoring, modelling and remote sensing (UNEP, 2021; GESAMP, 2019, 2021, 2024; Ministry Of Environment, Forest and Climate Change of India (MoEFCC), 2023). Such an approach includes developing global mass balance models (Borrelle and others, 2020; Harris and others, 2023), conducting advanced life cycle impact analyses (Casagrande and others, 2024) that also take into account the economic and ecological costs of emissions and releases into environmental compartments, and exploring blockchain technology (Gong and others, 2022). The key components of the comprehensive assessment approach include standardizing methodologies, improving plastic flow tracking and defining source-to-sea indicators, as well as assessing the impact of marine litter on wildlife and socioeconomic systems. Innovative approaches like monitoring the biota found on plastic, ingested microplastics, water-column micro- and nanoplastics (Moon and others, 2024) and seafloor imagery are also crucial (Sandra and others, 2023). GESAMP (2021) has highlighted the gaps in data on sea-based sources of marine litter and dumped plastics.



Simon Lorenz

6. Radioisotopes

Key points

- Assessments in the North-East Atlantic have found that discharges from nuclear power stations have continued to decrease since 2015. Comparable statistics are not compiled for other regions.
- Growing demand for non-carbon electricity has increased reliance on nuclear power, which is likely to lead to higher radioactive discharges.

Introduction

Radioisotopes in the ocean arise from both natural processes and anthropogenic inputs. Naturally occurring radioisotopes were examined in the first *World Ocean Assessment*, which continues to be the most recent global assessment available.

Developments since the publication of the second *World Ocean Assessment*, by source of anthropogenic input

Six main sources have led to anthropogenic inputs of radioisotopes to the ocean. An update since the publication of the second *World Ocean Assessment* is provided for each source.

Inputs from nuclear weapons testing

This source of inputs of radioactivity remains purely historical. However, the impact of nuclear weapons testing on the physical and mental health of Pacific Islanders remains evident (Patel, 2024; Pineda and others, 2023).

Inputs from nuclear incidents

There have been no significant nuclear incidents since the March 2011 incident at the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station. Efforts to deal with the contaminated water in the station were based on three principles:

- Removing contamination sources
- Redirecting groundwater away from contamination source
- Preventing leakage of contaminated water.

Measures to prevent leakage of contaminated water included the installation of a sea-side impermeable wall and a groundwater drainage system. This was installed to stop groundwater, which was ultimately pumped out, from flowing into the port area. These measures have led to the protection of the marine environment against pollution.

Japan has been analysing all water prior to its discharge into the sea to ensure that all radionuclides, other than tritium, are removed using an advanced liquid processing system (ALPS) and other systems to bring concentrations below regulatory standards. ALPS-treated water is discharged into the sea after being sufficiently diluted with seawater and after it has been confirmed that the concentration of tritium is below the regulatory standards. In the *IAEA Comprehensive Report on the Safety Review of the ALPS-treated Water at the Fukushima Daiichi Nuclear Power Station*, published in July 2023, the International Atomic Energy Agency (IAEA) concluded that the discharge of ALPS-treated water into the sea was consistent with relevant international safety standards and that the discharge would have a negligible radiological impact on people and the environment (IAEA, 2023a).[2]

Inputs from nuclear power plants

At the end of 2023, there were 413 nuclear power stations in operation worldwide, with a net electrical capacity of 373.7 GW (as compared with 450 stations with a capacity of 395 GW at the end of 2018) (IAEA, 2024). Assessments in the North-East Atlantic have found that discharges from nuclear power stations have continued to decrease since 2015 (OSPAR 2023, 2024). Comparable studies have not been conducted for other regions.

Discharges of tritium in cooling water are generally a significant component of radioisotope discharges from nuclear power stations, although they have relatively low radiological impact (Eyrolle and others, 2018). At present, industrial-scale abatement of tritium in cooling water discharges is not considered technically feasible (OSPAR, 2023).

[2] One country indicated that the report failed to fully reflect views from experts that participated in the review, and that the conclusion was not shared by all experts.

A substantial increase in nuclear electricity generation is expected in the coming decades, in response to the need to reduce reliance on electricity from fossil fuels. The IAEA projects that worldwide nuclear electricity generating capacity is likely to increase from 371 GW in 2022 to between 458 and 890 GW in 2050 (IAEA, 2023b). Because tritium discharges from nuclear power plants are generally related to the level of activity, it is likely that this increase will be accompanied by increases in tritium discharges.

Inputs from nuclear fuel reprocessing plants

Where data are available, discharges from nuclear fuel reprocessing plants continue to be substantially more significant than discharges from nuclear power plants (OSPAR, 2023). Six of the eight nuclear fuel reprocessing plants mentioned in the first and second World Ocean Assessments remain in operation. The plants in Tokai (Japan) and Sellafield (United Kingdom) have ceased operation (Japan Atomic Energy Agency (JAEA), 2023; Sellafield, 2022). A plant in Rokkasho, Japan, is expected to commence operations in 2026 (Japan Nuclear Fuel Limited (JNFL), 2024).

Inputs from industrial activities involving naturally occurring radioactive materials

There is no evidence of any significant global change since 2018.

Nuclear medicine

There is no evidence of any significant global change in the discharges from the clinical use of radiopharmaceuticals since 2018. However, the medicinal radionuclide and radiopharmaceutical market, as well as the theranostics market, are expected to grow. Furthermore, an increase in the use of outpatient procedures will mean an increased and uncontrolled excretion of radionuclides and their decay products into the environment (Pichler and others, 2025).

Changes in ocean due to the changing climate

It is highly likely that the impacts of climate change and ocean acidification will have many effects on the impacts of radionuclides on the ecology of the marine environment. Sea-level rise, which exacerbates the impacts of cyclones and storm surges, will likely impact some nuclear power plants; to date, however, most have continued to operate during storm events (Gwynn and others, 2024).

7. Conclusion

Although some positive changes associated with the impact of regulation on emissions and discharges of all types have been documented, it is apparent that the ocean contains a complex array of chemicals and materials due to human activities on land and at sea. Despite decreasing concentrations of some legacy chemicals, those that remain are now joined by new, emerging contaminants, which means that the ocean contains an increasing number of chemical types.

The mobile nature of the ocean and atmosphere means that chemicals and materials can be found far from their sources. Every geographical location on the planet is therefore affected by chemical contaminants to some extent.

Ultimately marine biota continue to be affected by a vast array of chemicals, some carried on plastics and others that leach from plastics. Although the understanding of the impact of chemicals, including plastics, is improving, it remains extremely limited. There is, however, a growing body of evidence that pollution has many adverse impacts that combine with other pressures on exposed marine biota. The cumulative effects of multiple types of pollution and other external pressures are resulting in significant changes to marine ecosystems.

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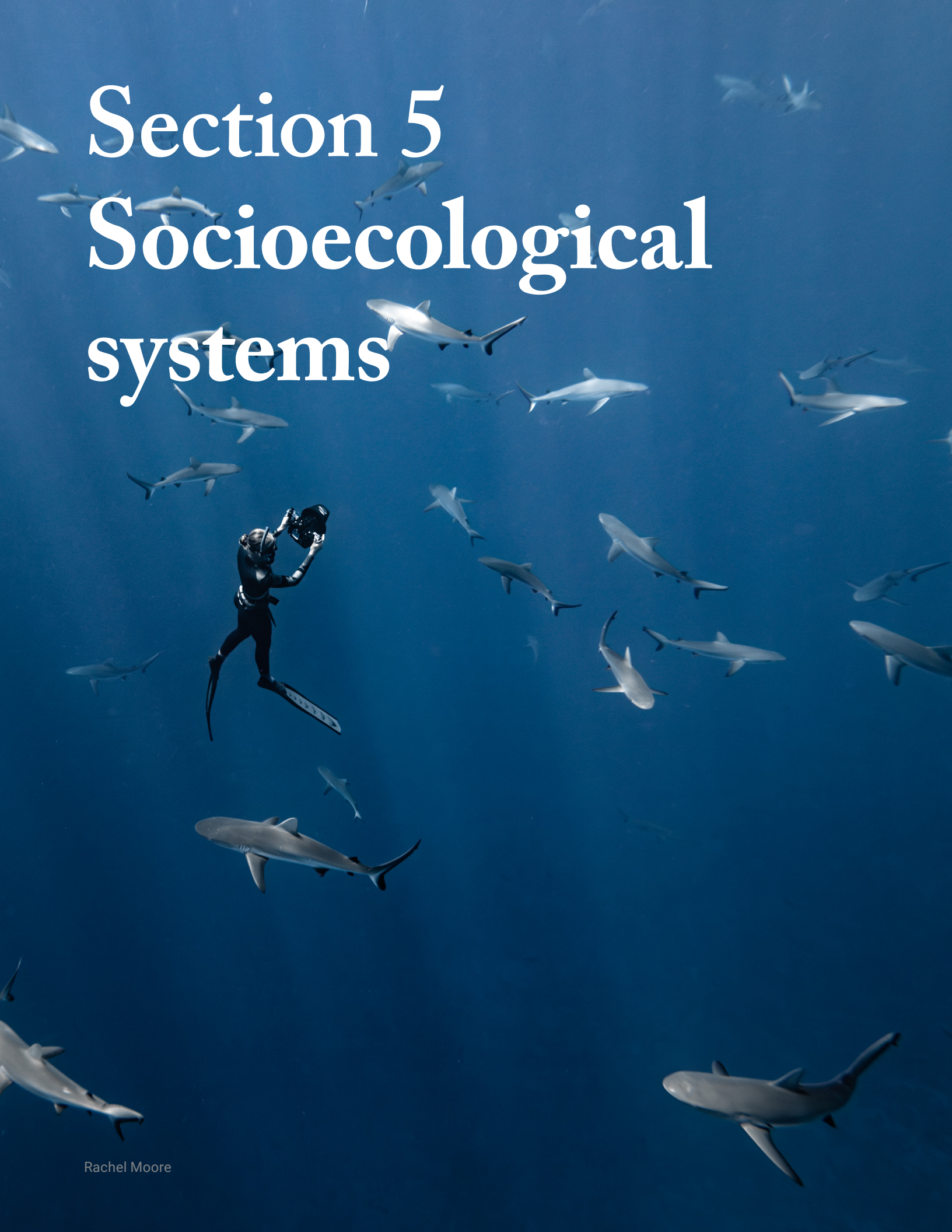
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Section 5 Socioecological systems



Rachel Moore

Introduction

The ocean is more than just a vast body of water – it is a dynamic, interconnected system where human societies and natural ecosystems are deeply intertwined. Human activities, from fishing and shipping to tourism and energy production, have a profound impact on marine ecosystems. At the same time, the ocean's health determines the well-being of communities worldwide, influencing food security, livelihoods and even public health. The present section contains an exploration of the complex socioecological systems of the ocean, emphasizing that sustainable management involves both conserving nature and ensuring the well-being of communities that rely on the ocean for their livelihoods.

The challenges facing the ocean today are multifaceted. Pollution, habitat destruction, overfishing and climate change place significant strain on marine ecosystems. Meanwhile, social and economic factors, such as demographic shifts, governance structures and technological advances, shape how these pressures manifest. The ocean is also a source of opportunity, with emerging solutions offering pathways to a more sustainable and inclusive future. The present section is aimed at providing a holistic perspective on these issues, assessing both risks and opportunities while proposing practical solutions.

The aim of the present section is to not only document challenges but also identify meaningful solutions. By integrating scientific insights, case studies and socioeconomic considerations, it outlines a road map for a future in which both people and the ocean can prosper.

The first subsection is focused on ocean economies – how marine resources are used and the systems in place to govern them. It includes an analysis of key sectors, such as fisheries and aquaculture, food trade, energy, shipping, tourism, biotechnology and coastal development, examining their impact on marine ecosystems and strategies for achieving sustainability.

The concept of a sustainable and inclusive ocean economy serves to emphasize the integration of economic growth, environmental stewardship and social well-being. In each chapter, the concept of sustainability pathways is applied to outline strategies for achieving the Sustainable Development Goals, including ecosystem restoration, governance improvements and sustainable marine resource management for future generations.

The second subsection has been structured around the One Health framework, a holistic approach aimed at striking a sustainable balance and optimizing the health of humans, animals and ecosystems. Under that framework, it is recognized that the health of humans, domestic and wild animals, plants and ecosystems are intrinsically connected and interdependent (One Health High-Level Expert Panel (OHHLEP) and others, 2022). Emphasis is placed on the importance of a thriving ocean for biodiversity and human health, including access to safe seafood, clean water and mental well-being. Issues such as marine pollution, zoonotic diseases and the role of coastal ecosystems in carbon sequestration are encompassed under this broad framework.

Equity, gender, justice and knowledge-sharing are key to shaping sustainable ocean futures. The second subsection also contains an exploration of how global challenges, such as pandemics, climate-related disasters and environmental injustices, affect communities differently. It highlights the importance of considering Indigenous, traditional owner and local community knowledge in building the evidence base for decision-making, as well as ways to ensure that ocean governance is fair and inclusive.

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Subsection 5A
A sustainable and inclusive ocean economy



Pavlos Evangelidis

Introduction

The present subsection, "A sustainable and inclusive ocean economy", consists of 10 chapters addressing key ocean sectors, the impacts of human activities, socioeconomic factors, governance frameworks and sustainability pathways aligned with global sustainability and inclusivity. Chapter 1 is focused on marine food systems and consists of six subchapters. The sustainable management of medium- and large-scale fisheries, which are highlighted in subchapter 1A, is critical due to their substantial ecological and economic impacts. The subchapter examines the severe environmental pressures caused by overfishing and habitat destruction, emphasizing the need for robust governance mechanisms, such as ecosystem-based management and stakeholder collaboration, to facilitate a transition to sustainable practices. Conversely, small-scale fisheries and aquaculture, discussed in subchapters 1B and 1D respectively, provide essential contributions to food security, livelihoods and cultural heritage. Those subchapters are focused on the socioeconomic importance of small-scale fisheries and aquaculture, which face threats from environmental changes. In those subchapters, emphasis is placed on governance strategies that integrate community-based approaches, including ecosystem-based management and traditional knowledge to improve resilience and promote fair resource management.

The role of emerging technologies, the challenges of climate change and the associated pressures on medium- and large-scale aquaculture, including those affecting the social acceptability of aquaculture or the ecological balance, are explored in subchapter 1C. The subchapter contains a discussion of related pressures, highlighting the importance of governance that actively engages local communities and applies data-driven management strategies. Subchapters 1E and 1F are focused on the processing and trade of seafood, integral components of the ocean economy that link production to global markets. Implementing sustainable practices in those sectors is crucial to minimizing environmental impacts, ensuring economic stability and advancing multiple Sustainable Development Goals. Those subchapters contain an examination of the environmental impacts of seafood processing and the associated resource depletion, emphasizing the need for governance that enforces strict processing standards and trade regulations.

The diverse uses of ocean spaces are highlighted in chapters 2 and 3, which are focused on recreational fishing and the energy sector respectively. Chapter 2 examines the ecological and socioeconomic impacts of increased recreational fishing activities in marine environments. Subchapters 3A and 3B, focused on energy from renewable and non-renewable sources respectively, draw contrasts between the carbon reduction potential of renewable energy and the environmental challenges posed by non-renewable energies.

The impacts of tourism, the potential of marine genetic resources and sustainability challenges in shipping are discussed in chapters 4, 5 and 6, respectively. Chapter 4 serves to highlight the dual role of tourism as an economic driver and environmental stressor, presenting governance strategies aimed at mitigating the sector's negative effects through sustainable practices and fostering eco-friendly tourism models that benefit local communities. Chapter 5 contains an exploration of the use of marine genetic resources, emphasizing governance frameworks that safeguard biodiversity and promote equitable benefit-sharing. Chapter 6 examines the significant environmental impacts of the shipping industry, stressing the urgent need for decarbonization strategies.

Chapters 7 and 8 cover emerging issues around marine mineral resources and the increasing reliance on desalination. The complex challenges of extracting marine minerals and the importance of sustainable practices and international cooperation are highlighted in chapter 7. Chapter 8 highlights technological and environmental challenges facing the desalination and salt production sector and the role of technologies that reduce energy consumption and manage waste effectively.

Lastly, sustainable coastal development and the need for a cautious approach to geoengineering are discussed in chapters 9 and 10. In chapter 9, pressures from urbanization and economic activities in coastal zones are discussed, along with the need for sustainable management strategies that serve to protect ecological health and enhance disaster resilience. The debate surrounding geoengineering as a climate mitigation approach is covered in chapter 10, which underscores the need for careful governance and international collaboration.

Chapter 1
Food systems

Introduction

Food systems[1] are facing a significant challenge: providing sustainable global food security and nutrition for a global population that is expected to reach almost 10 billion by 2050. Food systems are strongly affected by climate change, overfishing, infrastructure development and ecosystems degradation. They also contribute significantly to global climate change and biodiversity loss.

Seafood from wild fisheries and marine aquaculture accounts for around 20% of animal protein and 6.7% of total protein consumed by humans worldwide. In 2022, the production of world fisheries and aquaculture reached 223.2 million tons, including 185.4 million tons of aquatic animals and 37.8 million tons of algae. Human consumption accounted for 89% of total aquatic animal production and between 30% and 38% of total seaweed production (Food and Agriculture Organization of the United Nations (FAO), 2024). Marine food systems also provide livelihoods for many millions of people along the food supply chain and are strongly linked to cultural heritage and identity. As the world's population grows and average incomes rise, the demand for seafood will continue to increase. However, increasing seafood production depends on many environmental, ecological, social, economic, regulatory, governance and technological factors, as well as the complex interactions between them (Alexander and Kelling, 2024).

Given the significance of marine food systems, the present *World Ocean Assessment* includes a deeper analysis than the second *Assessment*, featuring the introduction of new subchapters on seafood processing and trade. The present chapter comprises six subchapters: medium- and large-scale fishing (subchap. 1A); small-scale fishing, including subsistence fishing (subchap. 1B); medium- and large-scale aquaculture (subchap. 1C); small-scale aquaculture (subchap. 1D); seafood processing (subchap. 1E); and trade (subchap. 1F). Together, they offer an updated assessment and outline key challenges in achieving sustainable marine food systems.

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[1] According to the High-level Panel of Experts on Food Security and Nutrition (2014), a food system is defined as all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socioeconomic and environmental outcomes.

Subchapter 1A
Medium- and large-scale fishing

Key points

- Medium- and large-scale fishing contribute to complex challenges within the marine environment, which underscores the need for tailored and sustainable management approaches.
- While medium-scale fishing plays a vital role in supporting local economies and livelihoods, large-scale fishing operations often present broader environmental and economic impacts.
- The literature emphasizes the importance of ecosystem-based management, transparency, traceability and stakeholder collaboration to mitigate the negative impacts of medium- and large-scale fishing.
- Effective governance structures, such as legal frameworks, co-management arrangements and adaptive management practices, are considered essential to ensuring that the medium- and large-scale fishing sectors contribute positively to sustainable development.
- Prioritizing effective governance structures can help to strike a balance between ecological conservation and economic objectives, fostering a more sustainable approach to the management of medium- and large-scale fisheries and, by extension, fisheries in general.

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1. Introduction

Fisheries are the backbone of many coastal economies and communities, providing livelihoods, food security and cultural identity (Srinivasan and others, 2012; Pollnac and others, 2015; first and second World Ocean Assessments). Major concerns about the state of fisheries have been reported, including concerns relating to stressors such as overfishing (Pauly and others, 2002; Food and Agriculture Organization of the United Nations (FAO), 2024); climate change (Intergovernmental Panel on Climate Change (IPCC), 2023) and pollution, including plastics (Lau and others, 2020). These multiple stressors have driven a concerted effort to strengthen the scientific understanding of the ecosystems, biodiversity, fishes and the economic, social and cultural activities that rely on them (Enevoldsen and others, 2022; Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), 2024; first and second Assessments), which has culminated in the third *Assessment* as the latest global synthesis of the state of the global ocean and regional seas.

The fisheries sector is diverse, consisting of a wide range of operations that vary significantly in scale and scope, technology, operational practices, environmental impact, sustainability measures, economic contributions and social dynamics (FAO, 1995; Sumaila and others, 2001; Gibson and Sumaila, 2017; Basurto and others, 2025). Small-scale or artisanal fishing is discussed in subsection 5A, subchapter 1B. Medium- and large-scale fishing entail different operational approaches, but both play an important role in the global fishing industry (see figure I).

Large-scale fishing is characterized by the use of large, high-capacity vessels, often exceeding 130 m in length, with a hold capacity of more than 2,000 tons (FAO, 1985). Such vessels are equipped with on-board facilities for freezing and processing seafood at sea, which enables them to remain at sea for extended periods and operate across thousands of miles (see figure I). Many vessels used in large-scale fishing are multipurpose, meaning that they are designed to operate two or more types of fishing gear without requiring significant modifications (Thermes and others, 2023). Large-scale fishing operations affect both continental shelf ecosystems and sensitive marine habitats owing to their spatial extent and intensity of activity (Jennings and Kaiser, 1998). However, it also means that the ability of management authorities to monitor their activities in parts of the ocean, especially in the waters of some countries of the global South, is limited.

Medium-scale fishing is carried out using medium-sized vessels, often at a regional scale (FAO, 1985). Medium-scale fishing operations serve as a bridge between artisanal or small-scale fishing operations (see subsect. 5A, subchap. 1B) and large-scale fishing operations, employing a variety of fishing methods and technologies (Halimatussadiah and others, 2023). Medium-scale fishing is carried out using vessels that are smaller than those used in large-scale operations but larger than traditional fishing boats, and the scope of operations is often regional (see subsect. 5A, subchap. 1B). Medium-scale fishing is more closely linked to national ownership of fishing vessels and domestic markets, often associated with relatively lower environmental impacts than large-scale fishing while providing a key support to regional and local economies. Although medium- and small-scale fishing are more easily monitored due to their smaller range of operations, they may result in higher intensity fishing in a smaller area, which leads to different environmental impacts that require careful management.

Figure I presents a comparison between medium- and large-scale fishing focused on key attributes that are discussed below.

One key distinction between medium- and large-scale fishing is technological sophistication, as moderately advanced technologies and mid-sized fishing gear are used in medium-scale fishing operations while highly advanced technology and gear are used in large-scale fishing operations (see figure I). Large-scale fishing fleets use advanced technologies that enable operations across wide oceanic areas, extending into remote, less-fished and ecologically sensitive regions (Norse and others, 2012), whereas vessels used for medium-scale fishing rely on a mix of traditional and modern methods and thus operate closer to shore.

It is worth noting that comparing the environmental impacts of medium- and large-scale fishing is not straightforward. Both have distinct environmental impacts that need to be carefully managed. When managing the environmental impacts of medium-scale fishing operations, focus needs to be placed on preserving local ecosystems. Medium-scale fishing operations are often more willing to adopt sustainable practices, and their closer

connection to local communities and ecosystems can be leveraged to promote the implementation of such practices to protect the environment. Meanwhile, with large-scale fishing operations there is a need to mitigate the potential of widespread environmental harm. Onboard observers and satellite tracking can be used to ensure the responsible operation of large-scale fishing operations. In both cases, sustainable fishing practices, stringent monitoring and regulation are vital to minimize the environmental footprint of fishing operations and ensure the long-term health of marine ecosystems (Pauly and others, 2002).

Figure I
Comparison of medium-scale and large-scale fisheries

Attribute	Medium-Scale Fisheries (MSF)	Large-Scale Fisheries (LSF)
Pressure on Fish Stocks	Moderate; concentrated regionally, may exert intense local pressure	High potential due to wide range, but spread over vast areas
Bycatch	Moderate to high; varies with gear type and practices	High; often associated with industrial trawling and purse seining
Overfishing Risk	High locally if not managed; often targets nearshore ecosystems	High due to volume and range; requires robust international oversight
Habitat Impact	Moderate; nearshore ecosystems more vulnerable to gear impacts	Potentially lower per unit area but higher in aggregate; risk to deep-sea and benthic habitats
Pollution (e.g., fuel, waste)	Lower to moderate; limited onboard processing	High; onboard processing and longer trips increase pollution footprint
Biodiversity Impact	Can be significant in confined areas	Potentially significant due to broader ecosystem interactions
Carbon Footprint	Moderate; shorter trips, smaller vessels	High; larger vessels, longer distances, heavy fuel consumption
Ecosystem Disruption	Focused and acute in local habitats	Broad-scale, chronic impacts if not regulated
Socioeconomic Impact	Strongly tied to local economies; supports community livelihoods	Generates large economic returns but benefits often concentrated in fewer hands
Economic Pressure	Medium; dependent on regional markets and subsidies	High; capital intensive, driven by global demand and market volatility
Illegal, Unreported & Unregulated Fishing (IUU)	Lower incidence; easier to monitor regionally	Higher risk due to remote operations and complex jurisdictions
Resilience to Environmental Change	Moderate to high; more adaptable and community-driven	Lower; high operating costs and rigid structures reduce adaptability
Dependence on Natural Resources	High; often lacks alternatives and depends on healthy local ecosystems	High; requires vast biomass to sustain operations
Monitoring & Regulation	Easier to enforce nationally; closer to shore	Difficult in distant waters; reliant on technology (e.g., satellites, observers)
Technology Use	Moderate; mix of traditional and modern gear	High; sophisticated gear, sonar, GPS, onboard processing
Operational Range	Regional; typically coastal or EEZ-based	Global; often in high seas, across jurisdictions
Link to Local Communities	Strong; supports local identity and food security	Weak; less embedded in local cultures
Sustainability Potential	Higher due to flexibility and community engagement	Moderate; scalable monitoring exists but implementation challenges remain

Sources: FAO, 1985; Jennings and Kaiser, 1998; Norse and others, 2012; Pauly and others, 2002; Halimatussadiah and others, 2023; Thermes and others, 2023.

2. Pressures and impacts

The pressures and impacts associated with large-scale fishing operations are greater than those associated with medium-scale fishing operations, which are usually limited to exclusive economic zones (EEZs). Sources of pressures and impacts from medium- and large-scale fishing include overexploitation, by-catch and discards, seafloor disturbances, pollution, unintended policy consequences, illegal activities, climate and global demand for seafood (for complementary discussions of pressures and impacts, see also sect. 3; sect. 4, subchap. 4D; and subsect. 5A, subchap. 1B).

Overexploitation

The environmental impacts of fishing activities can vary significantly between medium- and large-scale fishing operations (see figure I). Large-scale fishing vessels can stay at sea for extended periods, allowing them to fish in remote areas (Norse and others, 2012). Owing to the high capacity of the vessels involved, large-scale fishing operations continue to raise environmental concerns, including overexploitation of fish stocks, trophic cascades from predator removal, significant by-catch of endangered species, habitat destruction from fishing methods such as trawling, increased greenhouse gas emissions and marine pollution from lost or discarded gear (Gilman and others, 2020). The environmental impact of medium-scale fishing operations is often more localized, affecting the ecosystems where they operate. Nevertheless, their impact on local environments can be significant, particularly if they contribute to overfishing and habitat destruction.

Overfishing of species targeted by medium- and large-scale fishing is a major pressure on marine ecosystems, with overfished stocks increasing from 10% in 1974 to 37% in 2021 (FAO, 2024; Sharma and others, 2025). While overfishing is often assessed at the species level, it depletes entire ecosystems, making them more vulnerable to climate change impacts (Tam and others, 2017; Link and Watson, 2019; Sumaila and Tai, 2020). Any reduction in the abundance of high-value, high trophic level fish modifies the trophic chain and the flows of energy across ecosystems (Pauly and Christensen, 1995), which generates a social and economic impact on coastal communities.

Direct pressures from medium- and large-scale fishing vary by gear type, which include trawls and dredges, purse seines and longlines, gillnets and traps. The use of fish aggregating devices to enhance the efficiency and effectiveness of fishing gear has increased since the 1990s (Moreno and others, 2016). Fishing operations are profitable but they impose pressures on aquatic ecosystems, including habitat disruption and overfishing, and therefore regulation is essential (Bailey and Sumaila, 2015; Pittman and others, 2020).

Seafloor disturbances

The destruction and disturbance of benthic habitats caused by gear used in medium- and large-scale fishing, including trawls and dredges, can lead to a reduction in, or even the permanent loss of, the abundance and diversity of benthic and demersal organisms, due to changes in habitat structure, sediment displacement and disruption of food webs (Kaiser, 2019; Morris and others, 2023). Disturbance of carbon storage in the seabed can lead to the release of stored carbon dioxide (CO_2), potentially altering the nutrient cycle and sediment composition (Epstein and others, 2022).

By-catches and discards

Even though the increased use of by-catch reduction devices that are incorporated into fishing gears has decreased the overall rates of unintended capture of endangered marine life, such as birds, mammals, sharks and sea turtles, by-catch still persists in medium- and large-scale fishing (Chuenpagdee and others, 2003; Phillips and others, 2024; Barz, 2023; O'Keefe and others, 2023). Mitigation measures and by-catch reduction devices, including visual deterrents, fishing net mesh thickness, turtle excluder devices, circular hooks and ropeless fishing systems, have been shown to generally reduce by-catch with little significant effect on target catches (Huang and others, 2024).

Discards in medium- and large-scale fishing operations are another source of marine ecosystem impacts. Improved monitoring and reporting of discards and increased retention of non-targeted species will contribute to a better understanding of discards and, coupled with the use of more selective fishing gear, help to reduce the associated impacts (Lively and McKenzie, 2023).

Pollution

Ocean pollution, which ranges from plastic litter to oil spills and underwater noise, poses a major challenge to marine life and ecosystem health (Sumaila and others, 2012; Abbott and Sumaila, 2019; Lau and others, 2020). Underwater noise pollution is known to negatively impact the behaviour and physiology of marine species, including fish, invertebrates, mammals and reptiles (Di Franco and others, 2020). Studies have identified that vessel engines and propellers are the main sources of underwater noise, and steps need to be taken to encourage the incorporation of engineering mitigation measures into the design and specification of new vessels for medium- and large-scale fishing operations (Burella and Moro, 2021)

It is estimated that nearly 2% of all fishing gear, comprising 2,936 km^2 of gillnets, 75,049 km^2 of purse seine nets, 218 km^2 of trawl nets, 79,583 km of longlines and more than 25 million traps and pots, is lost annually in the ocean (Richardson and others, 2022). Abandoned, lost or otherwise discarded fishing gear, also known as ghost gear, is a substantial source of marine pollution and contributes to the entanglement of marine animals (Nama and Prusty, 2021). Gear loss varies by gear type, but estimates indicate that proportionately more gear is lost from smaller vessels (Richardson and others, 2022). Measures aimed at reducing the impacts of abandoned, lost or otherwise discarded fishing gear in the global oceans include biodegradable fishing gear, ghost gear reduction initiatives and eco-labelling certification programmes (McLennan and others, 2023).

Unintended policy consequences

Medium- and large-scale fishing operations might receive harmful subsidies for capacity enhancement, resulting in overcapacity and overfishing, which lead to social and economic consequences (Sumaila and others, 2024a). Since 1950, heavily subsidized fleets have expanded the total fished area from approximately 60% of the world's oceans to more than 90%. Over the same period, the average distance travelled from home ports has doubled, while catches per km travelled have declined to roughly only one third of the historical amount per km travelled (Tickler and others, 2018). A recent study found that 72% to 76% of the world's industrial fishing vessels are not publicly tracked, many of which engage in fishing around South Asia, South-East Asia and Africa (Paolo and others, 2024).

According to the most recent estimates, global fisheries subsidies totalled $35.4 billion in 2018, $22.2 billion of which was allocated specifically for capacity enhancement (Sumaila and others, 2019). In June 2022, after over 20 years of negotiations, the World Trade Organization (WTO) adopted an Agreement on Fisheries Subsidies aimed at prohibiting subsidies that contribute to illegal, unreported and unregulated (IUU) fishing, which threatens fish stocks. For the Agreement to take effect, however, two thirds of the 109 members of the Organization must formally ratify it by depositing their instruments of acceptance (Sumaila and others, 2024a).

Illegal, unreported and unregulated fishing and other illegal activities

IUU fishing represents a major threat to global fisheries governance, economic equity and marine sustainability. Each year, an estimated 8 million to 14 million metric tons of unreported fish are traded illicitly on global markets, generating gross revenues of $9 billion to $17 billion (Sumaila and others, 2020). The broader economic impact is even more staggering, with global losses due to the diversion of fish from legal markets estimated at $26 billion to $50 billion annually, resulting in $2 billion to $4 billion in forgone government tax revenues (Sumaila and others, 2020). High-risk areas for IUU fishing and labour abuse include the coasts of South America and western Africa, the north-western Pacific and the eastern tropical Pacific (Selig and others, 2022). The least developed countries are disproportionately affected due to systemic constraints, including limited financial resources, weak infrastructure, insufficient data systems and gaps in technical and enforcement capacity. In recognition of these disparities, several funding mechanisms have been developed to support the least developed countries and other developing countries in addressing IUU fishing. Examples include the Assistance Fund under Part IV of the Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA Assistance Fund), the voluntary WTO Fisheries Funding Mechanism Trust Fund (WTO, 2024), regional fisheries management organizations (RFMOs) and directed funds within such organizations, and direct bilateral support between countries. In response to the serious threats posed by IUU fishing, the global community has mobilized a suite of international efforts focused on monitoring, control and surveillance, enforcement,

and capacity-building and knowledge-sharing. Central among those efforts is the Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing (the Port State Measures Agreement), adopted under the auspices of FAO, which is aimed at preventing illegally caught fish from entering international markets by strengthening port inspection regimes and promoting information-sharing among States. The Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (the United Nations Fish Stocks Agreement) and RFMOs also play relevant roles in promoting cooperative enforcement on the high seas. Satellite-based vessel tracking, the Global Fishing Watch platform and observer programmes are increasingly being used to monitor activity in remote and transboundary waters. In addition, consumer-facing traceability initiatives and import regulations in key markets, such as the Catch Certification Scheme in the European Union and the Seafood Import Monitoring Program in the United States, are putting additional pressure on IUU actors by tightening access to markets. The success of such measures ultimately depends, however, on the political will, legal infrastructure and technical capacity of coastal States, especially in developing regions, to enforce compliance and prosecute violators.

Climate change

Medium- and large-scale fishing operations are driven by fossil fuel and thus contribute to global greenhouse emissions (Tyedmers and others, 2005; second *World Ocean Assessment*). The world's fishing fleets released 37.5 ± 7.4 million metric tons of CO_2 into the atmosphere between 1950 and 2014 (Mariani and others, 2020). Greer and others (2019) estimated that total CO_2 emissions in 2016 amounted to 159 million metric tons, which was much higher than estimates for previous years. When non-fishing activities such as transportation and preservation are included, total emissions associated with fishing operations are even higher.

Ocean warming, acidification and sea-level rise are affecting fish stocks and fishers in significant ways, including changes in the productivity and distribution of fish stocks, human migration to and away from coastal areas, stresses on coastal infrastructure for fisheries and challenges to maritime boundaries (Mendenhall and others, 2020; Gill and others, 2023). Climate change has caused substantial damage to and increasingly irreversible losses in fisheries yields. Ocean warming and ocean acidification have adversely affected food production from fisheries, and rebuilding overexploited or depleted fish stocks reduces negative climate change impacts on fisheries and supports food security, biodiversity, human health and well-being (IPCC, 2023)

Global demand for seafood

Expansion of fishing operations and pressures on fish stocks and marine ecosystems cannot be dissociated from the rapid increase in global consumption of aquatic animal foods. Globally, the amount of fish used for human consumption and for non-food use has increased from 28 million tons in 1961 to an estimated 185.4 million tons in 2022 (FAO, 2024). It has been well established that the production of fish meal (approximately 17 million tons per year), a major product used in fish feed in aquaculture, adds significant pressure on fish stocks and marine ecosystems (FAO, 2024).

3. Socioeconomic considerations

The present part contains an analysis of the social components of medium- and large-scale fishing through several global case studies, providing a perspective on employment, traditional knowledge, gender dynamics and the broader social impacts of industrialization and globalization. The social components of medium- and large-scale fishing encompass various aspects related to the individuals, communities and societies involved in, or affected by, fishing activities.

Employment and livelihoods

Wild fisheries generate significant employment worldwide (Kelleher and others, 2012). For example, in West Africa and South-East Asia, medium- and large-scale fishing operations generate significant employment opportunities directly in fishing activities and indirectly in ancillary industries, such as processing and marketing (Belhabib and others, 2015; Teh and Sumaila, 2013). Globally, some 260 million people are employed full- or

part-time by fisheries directly or indirectly, and medium- and large-scale fishing operations generate significant employment opportunities in the processing and export sectors in particular (Teh and Sumaila, 2013). However, there are differences in the benefits offered by large-scale industrial fisheries and those offered by small- and medium-scale fisheries, which have a more localized impact. In the case of large-scale fisheries, while their fleets may provide some employment opportunities, profits are often concentrated in corporate sectors, further marginalizing local fishers who rely on marine resources for their livelihoods (Srinivasan and others, 2010). In Indonesia, for example, large-scale fishing has contributed to declining fish stocks, which has resulted in significant job losses in local communities (Halimatussadiah and others, 2023).

The uneven distribution of benefits from large-scale fishing operations can also exacerbate economic inequalities. Profits from large-scale fishing fleets operating in developing countries, such as those in Africa and the Pacific, typically benefit foreign companies, with limited reinvestment in local economies (Pauly and others, 2014). The transnational nature of large-scale fishing, especially in regions such as the Indian Ocean and the South Pacific, often leads to the extraction of resources from developing regions to satisfy the demands of wealthier markets, creating local economic instability (Eriksson and others, 2015).

Cultural heritage and identity

Fishing is rooted in the cultural heritage of coastal and island communities worldwide. In many regions, traditional fishing practices have been passed down through generations, providing not only a source of sustenance but also a strong sense of cultural identity (Vave, 2022; Vave and others, 2024). The rise of medium- and large-scale fishing operations, however, has often displaced traditional practices, leading to a loss of marine cultural heritage. This pattern is evident in regions such as West Africa, where the expansion of large-scale fishing has eroded the cultural significance of small-scale fishing practices (Belhabib and others, 2015). In addition, traditional knowledge systems, which have long sustained marine ecosystems and fishing communities, are increasingly sidelined by the modern, technology-driven methods used in large-scale fishing (Teh and Sumaila, 2013). In the Pacific Islands, large-scale fishing methods are increasingly used in the place of traditional fishing methods that historically helped to maintain ecological balance and sustainability (Veitayaki, 1997). In parts of the Indian Ocean, the introduction of large-scale fishing has also changed the sociocultural fabric of fishing communities, as younger generations often seek employment in more economically lucrative sectors or leave fishing altogether (Eriksson and others, 2015).

For centuries, seafood has been an important component of Indigenous nutrition and food security (Cisneros-Montemayor and others, 2016), and traditional ecological knowledge has been a key component of sustainable fishing practices in many regions. Indigenous Peoples and local communities have developed sophisticated systems for managing fish stocks and maintaining ecological balance through such practices as rotational fishing and closed seasons (Drew, 2005). Traditional ecological knowledge, which is often closely linked to cultural heritage, plays a key role in promoting the social and environmental sustainability of fisheries. However, these traditional knowledge systems have been disrupted by the rise of large-scale fishing. In the Pacific Islands, traditional practices have been supplanted by the more efficient yet ecologically damaging methods employed by large-scale fishing fleets (Teh and Sumaila, 2013; Scherrer and others, 2024). The same dynamic is visible in parts of South-East Asia and Africa, where the expansion of large-scale fishing has marginalized the role of traditional ecological knowledge in fisheries management (Eriksson and others, 2015).

Gender dynamics and equity

Gender plays a central role in the social structure of fisheries worldwide (Harper and others, 2013; first *World Ocean Assessment*). In many regions, women are heavily involved in post-harvest activities, such as processing and marketing, while men often dominate fishing at sea (Lentisco and Lee, 2015). In West Africa, for example, women constitute a significant portion of the workforce in fish processing and trade. Nevertheless, their contributions are often undervalued in policy frameworks (Belhabib and others, 2015), and women frequently face gender-based disparities in employment, income and decision-making roles in fisheries (Oloko and others, 2024).

Gender inequalities have been exacerbated further by large-scale fishing operations because their focus on efficiency and mechanization often leads to the exclusion of women from traditionally female-dominated sectors, such as fish processing (Williams and Syddall, 2022). In the Pacific Islands, large-scale tuna fishing has led to significant gender disparities in the workforce, particularly in post-harvest sectors. In Fiji, women constitute

the majority of the workforce in tuna processing plants but remain concentrated in low-paid, repetitive roles with limited opportunities for career advancement (Syddall and others, 2022). In South-East Asia and the Pacific Islands, the roles traditionally played by women in the fisheries value chain are frequently marginalized, while large-scale operations tend to favour roles traditionally dominated by men, particularly in the management and technical sectors (Kleiber and others, 2015). Efforts to promote gender equity in fisheries need to be focused on ensuring that women have access to financial resources, training and leadership positions and on addressing gender-based barriers to employment.

Social impacts of industrialization and globalization

The industrialization and globalization of fisheries have led to significant social impacts, particularly in the developing world where fishing is a major source of livelihoods for millions of people. In large-scale fishing, which is driven by global demand for seafood, export markets are often prioritized, which can lead to the depletion of local fish stocks and threaten food security in developing countries (Pauly and others, 2014). In West Africa, the focus on exporting fish to international markets has reduced the availability of fish for local consumption, exacerbating poverty and malnutrition (Belhabib and others, 2015), while increasing income inequality, as profits from industrial fishing are concentrated in the hands of a few multinational corporations (Pauly and others, 2014). Other reported social impacts of industrialization include challenges such as increased migration, changes in local labour dynamics and the erosion of social cohesion in traditional fishing communities (Kleiber and others, 2015). The transnational nature of industrial fishing can lead to conflicts over resource use (Dahlet and others, 2021), particularly in areas where large-scale fishing operations directly compete with small-scale fishing operations (Pauly and others, 2014).

4. Sector-relevant governance

Effective governance of medium- and large-scale fishing requires robust legal and institutional frameworks supported by science-based management tools, international cooperation and adaptive policies that can be used to respond to environmental variability, market dynamics and technological change (Sumaila, 1999; Miller and others, 2013; Grip, 2017). Regulation must strike a balance between maximizing economic yield and minimizing ecological harm, including by-catch, habitat degradation and stock depletion. As noted above, regulating medium- and large-scale fishing activities is essential for mitigating adverse environmental and social impacts, particularly in shared or transboundary waters. Governance structures for medium- and large-scale fishing are embedded within international legal instruments, including the United Nations Convention on the Law of the Sea, the United Nations Fish Stocks Agreement and the Port State Measures Agreement, as well as a suite of binding and voluntary frameworks adopted by RFMOs and other global bodies. Those instruments establish the legal foundation for managing straddling and highly migratory stocks, regulating distant-water fleets, enforcing compliance and supporting transparency and accountability across jurisdictions.

Overlaps with the second *World Ocean Assessment*

In the second volume of the second *World Ocean Assessment*, the significance of the United Nations Convention on the Law of the Sea in advancing an integrated approach to ocean management and setting out the rights and obligations of States for the conservation and management of marine resources is highlighted. Reference is also made to the United Nations Fish Stocks Agreement, which builds upon the provisions of the Convention. With respect to fisheries management in particular, the discussion contained in the second *Assessment* is focused on the role of RFMOs and FAO guidelines, and not on management issues more generally.

International regulation

The international governance of marine fisheries is shaped by a constellation of legal instruments, institutions and policy frameworks that work collectively to manage the sustainable use of marine resources, especially in medium- and large-scale fishing. This governance regime encompasses legally binding agreements, voluntary instruments and their integration into the broader international environmental system.

Fisheries governance is anchored in the United Nations Convention on the Law of the Sea, which defines the rights and responsibilities of States over maritime zones, including territorial waters and EEZs. The Convention requires coastal States to ensure the conservation and sustainable use of fisheries within their EEZs and to cooperate in managing straddling and highly migratory stocks (White and Costello, 2014; Sumaila and others, 2015). Building on the Convention, the United Nations Fish Stocks Agreement is aimed at ensuring the long-term conservation and sustainable use of straddling and highly migratory fish stocks through effective implementation of the relevant provisions of the Convention. The Agreement promotes an ecosystem-based and precautionary approach to fisheries management (Pikitch and others, 2004), and provides for cooperation, including through RFMOs, for setting and enforcing conservation and management measures across the high seas.

Other instruments serve to further strengthen this governance regime, such as the Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas, which is focused on flag State responsibilities, and the Port State Measures Agreement, which helps to prevent fish caught through IUU fishing from entering markets by enhancing port inspections and enforcement (Bethel and others, 2021). These agreements collectively serve to curb IUU fishing and improve accountability in distant-water fishing operations. One major step forward is the WTO Agreement on Fisheries Subsidies, adopted in 2022, which prohibits the granting of subsidies to fleets engaged in IUU fishing, fishing of overfished stocks or fishing in unmanaged high-seas areas (Alger and others, 2023). Meanwhile, the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (2023), though not a fisheries treaty per se, introduces mechanisms such as area-based management tools and environmental impact assessments that may affect medium- and large-scale fishing operations in areas beyond national jurisdiction.

Beyond binding agreements, the Code of Conduct for Responsible Fisheries adopted by FAO in 1995 is a cornerstone voluntary framework. It encourages science-based stock assessments, selective fishing gear, compliance with international law and measures to protect coastal livelihoods. Under this framework, the Committee on Fisheries and FAO member countries have developed additional voluntary guidelines on such areas as by-catch reduction, small-scale fisheries and catch documentation, which are tailored to the evolving needs of global fisheries governance.

Fisheries governance is also increasingly influenced by global environmental treaties. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) regulates international trade in the marine species listed in its appendices, including the landing of specimens taken from areas beyond national jurisdiction, to ensure that trade is legal, sustainable and traceable. The Kunming-Montreal Global Biodiversity Framework includes explicit targets for sustainable fisheries, such as target 10. The relevance of climate-smart fisheries management was underscored in the documents transmitted by the secretariat of the United Nations Framework Convention on Climate Change to the General Assembly in 2023, and in the dialogues held at the seventeenth round of informal consultations on the United Nations Fish Stocks Agreement.

Although fisheries are not explicitly addressed as a stand-alone sector in the Paris Agreement, they are included in the economy-wide mitigation and adaptation commitments made by the Parties. In the outcome of the first global stocktake, emphasis was placed on the need for cross-sectoral emission reductions, including from fisheries-related activities. The alignment between fisheries governance frameworks and broader environmental governance frameworks demonstrates a growing recognition that sustainable fisheries management is crucial to climate resilience and global food security.

Regional and collaborative management

RFMOs play an important role in the management of high seas fisheries because they facilitate cooperation among States for the conservation and management of straddling and highly migratory fish stocks, establishing binding regulations to that end. They regularly adopt conservation and management measures addressing methods used in medium- and large-scale fishing, such as longlining and purse seining activities, and the associated impacts. While Cullis-Suzuki and Pauly (2010) have reported that not all RFMOs have been successful, more recently Sharma and others (2025) have indicated that there have been strong improvements in the management of tuna fisheries under RFMOs.

Co-management and adaptive management are integral approaches to the effective governance of large-scale fishing (Jentoft, 2005). Co-management involves shared

governance, in which responsibilities and authority for managing fisheries are distributed across various stakeholders, including government agencies, local communities and industry representatives (Wilson and others, 2003). For example, salmon fisheries in Alaska, United States, are managed through a co-management approach that includes state and federal agencies, native Alaskan organizations and commercial and sport fishers (Pinkerton, 1994).

Management at the domestic level

Domestic management of marine fisheries is foundational to achieving sustainability because most commercially exploited fish stocks are found within the confines of national jurisdictions. Coastal States have sovereign rights and responsibilities over resources within their EEZs, and flag States maintain primary jurisdiction over vessels flying their flag on the high seas (Miller and Sumaila, 2014). This makes national fisheries regulation essential not only for domestic sustainability, but also for supporting and reinforcing international and regional governance regimes.

National governments deploy a range of management tools, such as licensing programmes, total allowable catch limits, gear and spatial restrictions and enforcement mechanisms, to regulate medium- and large-scale fisheries. In some cases, however, sustainable fisheries management is not prioritized in such policies, which are instead focused only on economic growth, foreign exchange earnings or industrial development. This can result in the marginalization of small-scale fisheries and the degradation of marine ecosystems.

In recent years, reforms of domestic legal frameworks have been increasingly undertaken to address such challenges. For instance, several coastal States, in particular those within the area designated by FAO as Major Fishing Area 51, have updated national fisheries laws to include specific provisions regulating fish aggregating devices in response to concerns over gear proliferation and by-catch (Gomez and others, 2020; Barston, 1999). National legislation has also played a key role in supporting the establishment and regulation of marine protected areas (MPAs), in alignment with global commitments to protect 30% of the ocean by 2030. Many countries are now strengthening laws that manage the interactions between medium- and large-scale fishing operations and sensitive marine ecosystems.

The effectiveness of domestic fisheries governance increasingly depends on transparency and innovation in monitoring, control and surveillance. Coastal States are adopting technologies such as automatic identification systems and vessel monitoring systems to enhance real-time vessel tracking and compliance monitoring (Merten and others, 2016; Kuemlangan and others, 2023). While use of automatic identification systems was initially limited, legal mandates and international cooperation have expanded the uptake of this technology and data-sharing. Under the International Declaration on Transnational Organized Crime in the Global Fishing Industry (the Copenhagen Declaration), coastal States commit to strengthening international cooperation, information-sharing and law enforcement coordination to more effectively address IUU fishing and other forms of transnational fisheries crime (Bunwaree, 2023). Some RFMOs, including the Indian Ocean Tuna Commission (IOTC), take a similar approach to monitoring fishing vessels, for example through the implementation of stock rebuilding plans. Efforts are currently under way within IOTC to establish a quota allocation system based on total allowable catch, which is expected to be adopted in 2027. IOTC has adopted measures to strengthen management of drifting fish aggregating devices through the implementation of more environmentally friendly designs, drifting fish aggregating device registries and tracking systems.

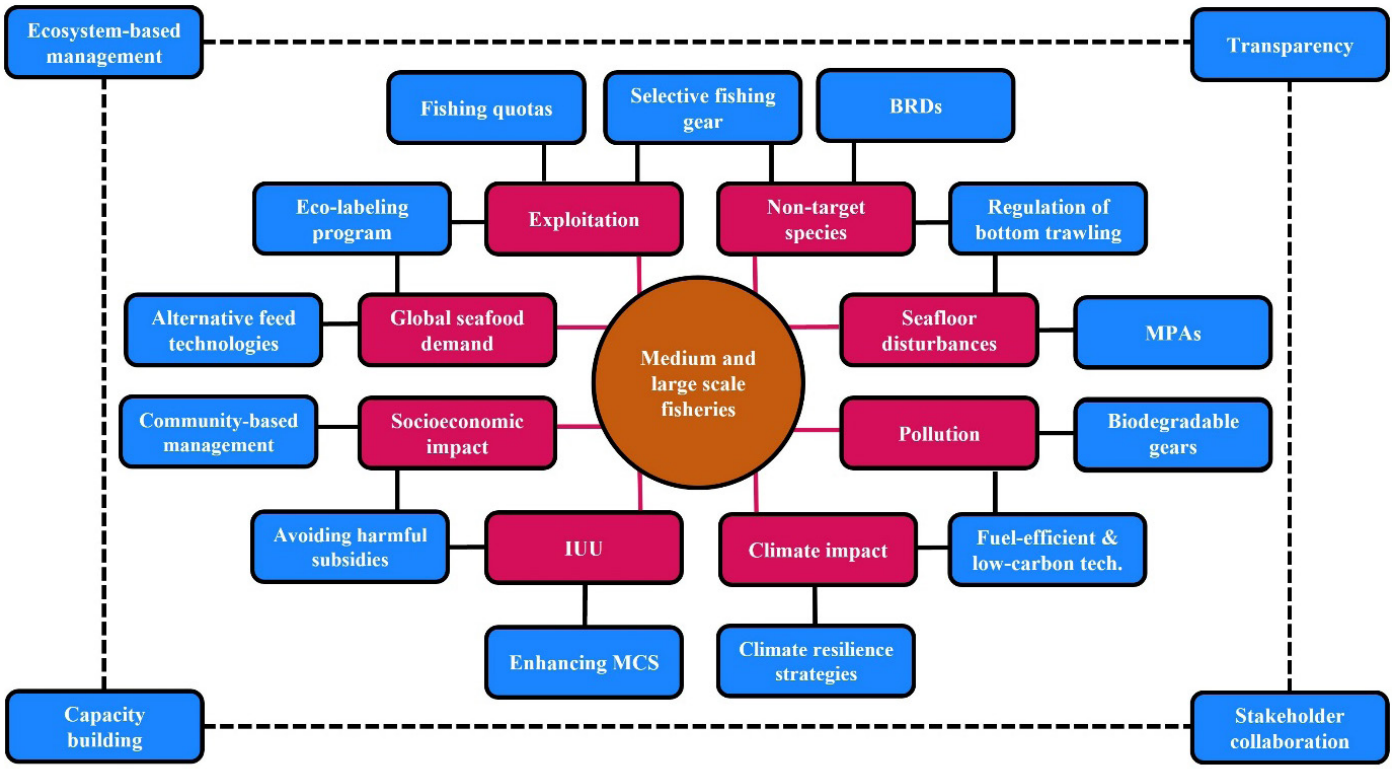
RFMOs sometimes revise their conservation and management measures, which can overwhelm smaller domestic fleets that may lack the capacity to adapt quickly. This highlights the importance of adaptive management, phased implementation and stakeholder consultation at the national level. National-level fisheries management is not only central to safeguarding marine biodiversity and food security, but also to ensuring equity and resilience in the face of growing challenges like climate change and overfishing. Integrating ecological, economic and social objectives, such as the promotion of the rights and participation of small-scale fishers and Indigenous communities, can lead to more effective, inclusive and forward-looking fisheries governance (Sumaila, 2021; Naylor and others, 2021).

5. Sustainability pathways

The sustainability of medium- and large-scale fishing is vital for maintaining the long-term health of marine ecosystems, ensuring the livelihoods of the millions of people who depend on these resources (Teh and Sumaila, 2013; FAO, 2024), and supporting the economic stability of global fishing communities. Achieving sustainability requires an interdisciplinary approach that integrates ecological, social and economic considerations (Murphy, 2011; Sumaila, 2024).

The present part is aimed at articulating possible pathways to achieve the vision of a sustainable ocean in 2050. The information provided will help policymakers and managers to understand the tools available and how such tools could be utilized to move beyond existing systems of human use of the ocean, otherwise known as the business-as-usual scenario, or incremental change to that scenario and towards a transformative reorganization (see figure II).

Figure II
Sustainability pathways for medium- and large-scale fisheries



Source: Prepared by the writing team.

Note: The sustainability pathways, shown in blue, are matched with the pressures and impacts, shown in red.

Abbreviations: BRDs, by-catch reduction devices; IUU, illegal, unreported and unregulated fishing; MCS, monitoring, control and surveillance; MPAs, marine protected areas.

The following parts contain a discussion of what needs to be done to put medium- and large-scale fisheries on the path to real sustainability (Roberts and others 2024; "Vision 2030"; for a discussion of sustainability pathways for small-scale fisheries, see subsect. 5A, subchap. 1B) to achieve the vision of a sustainable ocean by 2050.

Reducing overcapacity and overfishing

Overcapacity, a situation in which fishing fleets are able to catch more fish than ecosystems can sustainably produce, is one of the most persistent drivers of overfishing and the degradation of marine ecosystems (Pauly and Christensen, 1995). The deployment of too many vessels

or too much gear in pursuit of limited fish stocks not only results in biological overexploitation, but also intensifies competition, diminishes profitability and increases harmful environmental impacts, such as habitat destruction and excessive by-catch. Reducing overcapacity is therefore essential for restoring ecological balance and ensuring the long-term sustainability of fisheries. Policy interventions, such as fleet reduction programmes that may include decommissioning or buy-back schemes, can help align fishing efforts with the productive capacity of marine ecosystems. However, such measures must be carefully designed to avoid rebound effects, such as reinvestment in more efficient vessels. They should also be paired with socially just transition strategies, including retraining programmes, alternative livelihoods and financial support for affected communities (Clark and others, 2005, 2007). This is particularly important in coastal areas where fishing is a cultural mainstay and economic lifeline.

One approach to controlling overfishing that can complement fleet size reduction is the use of effort-based management systems, which include limits on the number of fishing days, gear restrictions, closed seasons and MPAs to enable stocks to replenish (Roberts and others, 2024). These tools are especially valuable in contexts where the data required for implementation of total allowable catch systems are limited or unreliable. Rights-based approaches, such as territorial use rights in fisheries and individual transferable quotas, can also be used to help to align conservation incentives and reduce the race to fish, if designed carefully (Sumaila, 2018).

To be effective, efforts to reduce overcapacity must be embedded within transparent governance frameworks that include science-based decision-making, monitoring, control and surveillance systems and meaningful participation by small-scale fishers and Indigenous communities. Well-managed overcapacity reduction measures not only help to rebuild fish stocks and protect marine biodiversity but also contribute to more stable livelihoods, better food security and healthier ocean ecosystems.

Subsidy reform and investment in education and capacity-building

Perverse financial incentives, such as harmful subsidies, promote overfishing and environmental degradation (Milazzo, 1998). Subsidy reform is a critical step towards achieving sustainable fisheries management, aligning economic incentives with that goal and preserving the livelihoods of communities that depend on healthy marine resources (Sumaila and others, 2010, 2024a; Skerrit and others, 2023; Villasante and others, 2024). Incentivizing compliance with conservation measures and participation in sustainable certification programmes can promote long-term ecological health (Roberts and others, 2024). The subsidy allocation process should be reviewed. Consideration should be given to granting subsidies to operations that use energy-efficient vessels or fishing methods or to individual skippers who prioritize considerations other than the catch or who invest in energy-efficient strategies (Bastardie and others, 2022). Nevertheless, subsidies have to be designed carefully or they may backfire (Clark and others, 2005).

The decarbonization of the fishing sector will require enormous financial resources that the sector alone cannot provide. Investments are needed in education, training, capacity-building and knowledge-sharing, which are crucial for empowering stakeholders to adopt sustainable practices (Lennie, 2005). Training programmes on new technologies, sustainable fishing techniques and resource management are necessary to improve fisheries management (Bradley and others, 2019). Empowering women and young people through education can lead to more inclusive and resilient fisheries (Stacey and others, 2019). Capacity-building and knowledge-sharing help communities to adopt new technologies, improve safety at sea and foster innovation, contributing to healthier ecosystems and improved livelihoods (Vierros and others, 2020). By strengthening the skills of those involved in fisheries, education promotes long-term sustainability (Macfadyen and Huntington, 2004).

Stakeholder collaboration and knowledge co-creation

Collaboration between Governments, industry, non-governmental organizations (NGOs) and local communities is key to sustainable fisheries management (Pomeroy, 1995). Co-management approaches, in which responsibilities for resource management are shared, have been proven effective in many regions. Partnerships between governments, industry, local communities and NGOs facilitate the sharing of best practices and drive innovation in sustainable fishing practices (Jentoft, 2005). One area of emphasis under the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) is the co-creation of knowledge for the oceans of the future, which entails incorporating the perspectives of fishers and local stakeholders into fisheries governance with a view to achieving better compliance and more effective

management strategies (Chambers and others, 2021; Norström and others, 2020). Consumers also play a crucial role in fisheries management through their purchasing choices, advocacy and demand for sustainable seafood. A good example of an initiative aimed at mobilizing consumers to promote more sustainable fisheries management is the awareness-raising campaign by the Ocean Literacy initiative of UNESCO.[1]

Indigenous and community-based fisheries management practices, rooted in traditional ecological knowledge, offer valuable insights into sustainable resource management (Berkes and others, 2007). Integrating traditional knowledge into modern fisheries governance enhances sustainability and resilience. There is a need for countries to recognize the cultural importance of local knowledge and stewardship by supporting Indigenous and community-based fisheries management practices through policy and funding. Empowering Indigenous communities fosters stewardship, protects cultural heritage and promotes sustainable livelihoods. Community-based management improves compliance rates and enhances resilience by ensuring that conservation measures are culturally appropriate and effective (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019, 2022, 2024). The best way to support Indigenous and community-based fisheries management is to encourage vessels engaged in medium-scale fishing to operate in open-ocean areas that are further from such communities and therefore less frequently fished by them. Based on community consultations in Fiji, fishers occasionally report seeing large vessels fishing outside outer reef boundaries for bait. This can affect local bait availability or potentially increase by-catch rates of community important species, including species used for food, and culturally important species, such as turtles and sharks. A survey of catch from select landing sites in Fiji showed that most reef fish were consumed by fishers, while oceanic species were sold (Marre and Hunt, 2022).

Technology

Selective fishing gear plays a crucial role in reducing by-catch, the unintentional capture of non-target species, including juveniles and endangered species (Cook, 2003). The use of selective gear, such as circle hooks and turtle excluder devices, enables fishers to target specific species and sizes, minimizing harm to marine ecosystems (Condie and others, 2014). Selective fishing gear reduces the capture of juvenile fish, allowing populations to reproduce and grow, thereby supporting the recovery of depleted stocks and maintaining biodiversity. Incentives are crucial to encouraging fishers to adopt more selective practices, as discard bans alone may not lead to more sustainable outcomes without adequate motivation (Condie and others, 2014; Villasante and others, 2016).

Traceability systems enable the tracking of fish products from catch to consumer, ensuring that the products are sustainably sourced (Thompson and others, 2005). Electronic monitoring, in which cameras, sensors and the Global Positioning System (GPS) are used to record fishing activities, is a cost-effective tool for enhancing compliance, data collection and transparency in fisheries management. Electronic monitoring can improve oversight where on-board observers are limited. Nevertheless, there are barriers to the adoption of such technologies, including high upfront costs, data privacy concerns, lack of technical capacity and resistance by some fishing operators who are wary of increased scrutiny and regulatory burdens. Technologies such as blockchain and electronic catch documentation enhance transparency in the supply chain and help to combat IUU fishing. These technologies also provide consumers with the information needed to make informed choices, driving demand for sustainable seafood. Transparency in fisheries also reduces IUU fishing, which costs the global economy billions and threatens marine ecosystems (Agnew and others, 2009; Sumaila and others, 2020). Digital traceability platforms and certification programmes enhance trust among stakeholders and promote long-term sustainability (Blaha and others, 2023). Artificial intelligence is now being used to help different sectors to implement tools for sustainable practices. Leveraging the power of artificial intelligence, these innovative approaches are aimed at revolutionizing the fishing industry by enhancing efficiency, sustainability and overall productivity (Pereira and others, 2023).

Governance

The governance of marine fisheries is fundamental to ensuring the sustainability of global marine resources, particularly in the context of medium- and large-scale fishing,

[1] See https://oceanliteracy.unesco.org/.

which account for a significant share of global catch and economic activity (Österblom and Folke, 2013). Owing to the complex and dynamic nature of marine ecosystems, coupled with the highly mobile behaviour of many target species and the diverse and often conflicting interests of industrial, semi-industrial and artisanal sectors, tailored, multiscale governance approaches are required (Mora and others, 2009; see also sect. 3).

Policy

Ecosystem-based fisheries management entails a comprehensive approach in which consideration is given to the entire ecosystem, including human impacts, instead of managing single species in isolation (Tam and others, 2024). This strategy addresses interdependencies between species, habitats and human activities, promoting ecological balance. Protecting critical habitats, such as coral reefs and mangroves, is central to the success of ecosystem-based fisheries management, which is aimed at striking a balance between ecological, economic and social objectives. Various practical approaches to ecosystem-based fisheries management have been developed and applied globally as tools to achieve the targets for Sustainable Development Goal 14 (Link and Marshak, 2021; Hobday and others, 2011; Zhang and others, 2011), but implementation has been slower than expected in many regions (Fletcher and Bianchi, 2014; Patrick and Link, 2015).

Fishing quotas and catch limits are fundamental tools for sustainable management of fish stocks (Walters and Martell, 2002). Grounded in scientific data, they ensure that fish populations can replenish at sustainable rates. Science-based quotas must be flexible and adaptive, reflecting changes in stock health and ecosystem dynamics (Holsman and others, 2020). Monitoring and enforcement mechanisms, such as satellite tracking and on-board observers, are necessary to ensure compliance with quotas and to prevent illegal fishing activities (Paolo and others, 2024).

Clear communication about the trade-offs, uncertainties and risks involved in fisheries management is essential for informed decision-making (Booshehrian and others, 2012). The involvement of fishers, scientists, policymakers and the public enables a clearer understanding and more effective management of the trade-offs between short-term economic gains and long-term ecological sustainability. Developing risk management strategies that account for uncertainties in fish stock assessments and market fluctuations can mitigate potential negative outcomes (Roux and others, 2022).

Ecosystem-based fisheries management, implementation of fishing quotas and catch limits, and effective communication of trade-offs, uncertainty and risks contribute to ensuring the sustainability of medium- and large-scale fisheries, as these approaches are intended to work together to preserve marine biodiversity while maintaining global seafood supplies. This goal is achieved by leveraging innovative technologies, integrating adaptive policies, promoting stakeholder collaboration and providing socioeconomic support in the context of a changing climate (Sumaila and others, 2024b).

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Subchapter 1B
Small-scale fishing, including subsistence fishing

Key points

- Small-scale and subsistence fisheries make substantial contributions to national and global economies and are socially and culturally important.
- The cumulative effects of a wide range of drivers, including social, economic, environmental and climate drivers, pose significant threats to the viability and resilience of small-scale and subsistence fisheries globally.
- Sustainable pathways for small-scale and subsistence fisheries must address the cumulative effects of multiple drivers of vulnerability, build on knowledge and experience, and take into consideration equity, human rights and security concerns.

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1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication* were ratified in 2014 (FAO, 2015), providing a road map aimed at reinforcing sustainable small-scale and subsistence fisheries and their multidimensional contributions (food security and income generation) along the value chain (i.e. the nodes and networks of activity that yield value from pre- and post-harvest processing and marketing activities) (Jentoft and others, 2017; Arthur and others, 2022; Nakamura and others, 2021; Basurto and others, 2025). The contributions of small-scale fisheries to the 2030 Agenda for Sustainable Development and the Sustainable Development Goals, as well as to the implementation of the Kunming-Montreal Global Biodiversity Framework, have been increasingly recognized (Charles and others, 2024). However, small-scale fisheries tend to be economically vulnerable and politically marginalized in global policy debates (Jentoft and others, 2022).

There is no globally agreed definition of small-scale fisheries, but they can be characterized as place-based and primarily for family consumption (low production), with limited capital or resource inputs, but labour-intensive and based on trips that are spatially and temporally limited (i.e. close to shore or completed within a day) (FAO, 2018). Individual nation States have adopted a wide range of definitions linked to gear type (i.e. type and size of nets), length of boat and means of power, vessel ownership, trip duration and area of fishing activity (e.g. inshore or nearshore) (Pita and others, 2020; Smith and Basurto, 2019), as shown in the table below. Small-scale fisheries undertake pre-harvest activities (e.g. preparing gear or planning), harvesting of fishery resources and post-harvest activities (e.g. marketing or trading). Activities along the value chain are undertaken by both men and women (Rosales and others, 2017; Pradhan and others, 2022; Galappaththi and others, 2023).

Table
Selected attributes and elements of small-scale fisheries

Attribute	Related elements	Examples
Indicative gear	Fishing gear	Labour-intensive gear Passive gear
	Mechanization	No mechanization Small power winch (hauler powered off engine)
Vessel	Size of fishing vessel	No vessel Less than 12 m, or 12–24 m
	Motorization	No engine Engine less than 100 hp, or 100–400 hp
Operation	Fishing trip duration	Less than 6 hours Day trip 1–4 days
	Fishing location and range	Less than 100 m from shore Up to 10 km offshore 10–20 km offshore
Storage/preservation	Refrigeration/storage	No cold storage Ice box on board Ice hold below deck
Employment/labour	Labour crew	Individual or family Cooperative group Small number of employed crew
	Ownership	Owner or owner-operator Lease arrangement
	Time commitment	Occasional Full-time seasonal or part-time all year Full-time

Table (*continued*)

Attribute	Related elements	Examples
Use of catch	Disposal of catch	Household consumption or barter exchange Direct sale at landing site(s) Sale to traders (intermediaries)
	Utilization of catch, value addition, preservation	For direct human consumption Chilled, locally processed, cured/salted/dried Frozen (temporarily)
	Integration into economy and/or management system	Informal, non-integrated (no fees) Integrated (registered, untaxed) Formalized (licensed, landing fees)

Source: Adapted from FAO, Duke University and WorldFish, 2023.

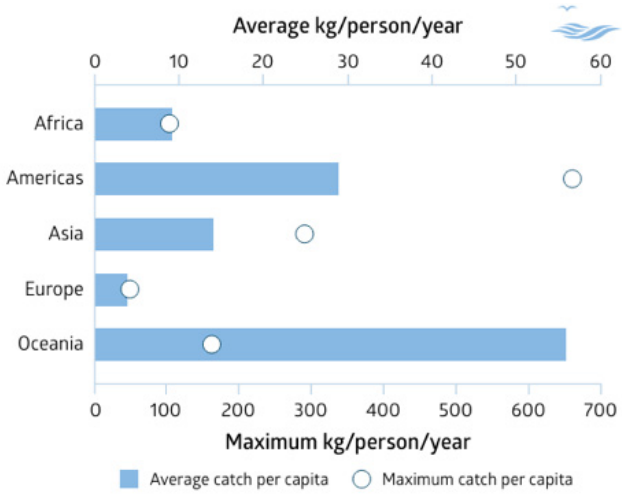
There are numerous exceptions to the attributes reflected in the table above (FAO, 2015; Smith and Basurto, 2019). Identification of the size, scope and scale of fishery operations is recommended in order to improve policy implementation (e.g. access and tenure, marketing, economic policy, regulation and enforcement) and to enhance evidence-based and comparative assessment. However, definitions of small-scale fisheries do not fall within an immutable category fixed in time and space. Rigid adherence to a specific definition is neither possible nor desirable.

The economic, social and cultural importance of small-scale fisheries is very well established (Chuenpagdee and others, 2017; Dias and others, 2023; Berkes and Franz, 2025). Total landings of all species by marine small-scale fisheries are estimated at 25.1 million tons per year, or approximately 40% of global landings, with an estimated annual revenue of approximately $77 billion (FAO, Duke University and WorldFish, 2023). There are significant regional variations in total catch per capita (see figure I). Oceania has the largest average annual marine catch per capita, while Europe has the lowest. However, regional variations in catch per capita do not necessarily indicate relative importance. Despite lower catch per capita levels, small-scale fisheries in Africa and Asia are of crucial importance because of the overall number of fishers in the sector.

Small-scale fisheries' contributions are different for men and women, highlighting the importance of gender analysis in small-scale fisheries policy (Lawless and others, 2021; Okafor-Yarwood and others, 2024a). Small-scale fisheries contribute to poverty alleviation and viable livelihoods and are linked to cultural identity and stewardship (Arthur and others, 2022; Béné and others, 2016; Mangubhai and others, 2023). They are also important for food security and nutrition (e.g. vitamin B12, calcium and important fatty acids) and provide an average of 17% of the nutrient supply globally (Viana and others, 2023; Basurto and others, 2025).

Figure I

Global estimates of marine small-scale fisheries' catch per capita, by region (average annual values, 2013–2017)



Source: FAO, Duke University and WorldFish, 2023.

2. Pressures and impacts

Significant pressures and impacts on small-scale fisheries include: (a) economic growth and coastal development (Brent and others, 2020); (b) overfishing, environmental impacts and climate change (Ruiz-Díaz and others, 2020); (c) competition with medium- or large-scale fisheries sectors, including illegal, unreported and unregulated (IUU)

fisheries and marine security/boundary issues (Ayilu and others, 2023; Okafor-Yarwood and others, 2024b); (d) loss of access catalysed by efforts to meet marine conservation targets (Bennett and others, 2021a); (e) global trade and competition for market access (Schuhbauer and others, 2019); and (f) policy and governance shifts (Sowman and Sunde, 2021; Berkes and Franz, 2025) (see sect. 4, chap. 1). The heterogeneity of small-scale fisheries, non-standardized approaches to data collection and analysis, and a lack of data collection generally across a range of environmental drivers affecting small-scale fisheries limit the fine-grained assessments that are necessary to support targeted policy interventions.

Most Member States with ocean areas within their national jurisdiction have adopted or are adopting strategies or regulatory frameworks related to ocean use and planning in order to catalyse economic growth and coastal development. Investments in marine sectors by financial institutions and other donors in Latin America, for example, expanded considerably between 2012 and 2020 (Gerhardinger and others, 2022). Investment strategies rarely include the participation of small-scale fisheries organizations (Schuhbauer and others, 2020). Evidence that poorly structured coastal and ocean economic development policies have a negative impact on small-scale fisher communities is established but incomplete (Bennett and others, 2021a; Ertör, 2023; Jentoft, 2022; Okafor-Yarwood and others, 2020). Ocean "grabbing" (i.e. securing ocean space) by private and/or State actors may create significant injustices through a set of displacement and dispossession processes targeting fisher communities, and may sometimes be in conflict with customary tenure and access rights (Ertör, 2023; The Ocean Defenders Project, 2025). These social processes exacerbate the effects of sea-level rise, including tidal flooding and erosion (Gonzalez-Mon and others, 2021), which already drive displacement and migration decisions. The displacement and/or migration of communities from their fishing territories to different locations creates social challenges given the strong sense of place of most small-scale fishing communities (Cánovas-Molina and others, 2022; FAO, Duke University and WorldFish, 2023; Okafor-Yarwood and others, 2020; Queffelec and others, 2021).

Plans for new ports, tourist facilities, shipping lanes and security zones, oil rigs, mining areas, wind farms and new aquaculture ponds can also encroach upon geographical, political and economic territorial spaces and have a negative impact on the environment on which small-scale fishers rely. Offshore hydrocarbon operations affect wild-capture fisheries by displacing fish stocks and altering fish biochemistry, and submarine pipelines and cables may also hinder the activity of small-scale fisheries (Jouffray and others, 2020). The growth of offshore sea mining will have significant impact on habitats, including the discharge of sediments and metals into the water column (United Nations Environment Programme (UNEP), 2022), which will have a negative effect on ecosystems and small-scale fisheries. The negative impacts of underwater noise, vibration and electromagnetic waves from large wind farms on fisheries resources have also been identified (Oh and others, 2021).

The cumulative effects of environmental and climate drivers on the viability of small-scale fisheries are very well established (Brent and others, 2020; Evans and others, 2023; Louey, 2022). Fish disease, habitat degradation, invasive species and loss of species diversity were identified as important environmental drivers affecting small-scale fishers across 12 focal countries in Asia and Africa (Dias and others, 2023). The livelihoods of small-scale fishers depend on aquatic and marine environments. The conditions of these ecosystems, such as water quality, temperature and salinity, are crucial for their sustainability. Environmental degradation, such as pollution from domestic, industrial, agricultural and aquaculture waste, and poor watershed management can adversely affect these conditions, threatening the viability of small-scale fisheries (Nayak and others, 2014; Martínez-Vázquez and others, 2021; Evans and others, 2023). Variations in water quality across geographical areas can affect the accessibility and availability of fish.

Macroplastic and microplastic pollution (fragments and fibres) has emerged as a crucial challenge for coasts and fisheries, with human health implications (Barboza and others, 2018; Rochman and others, 2015; Smith and others, 2021). Evidence of the relationship between microplastics and small-scale fisheries is established but incomplete, yet research points to an environmental driver affecting a diverse range of fisheries and ecosystems (e.g. pelagic, demersal and benthic zones), with negative implications for the fisheries. For example, Savoca and others (2021) estimate that plastic ingestion is occurring in 386 species of marine fish globally, while Pellini and others (2018) indicate that about 95% of fish analysed in the Adriatic Sea were observed to contain microplastics. A study in Puerto Morelos, Mexico, in 2024 recorded high levels of microplastics in commercial reef species, many of which make up a significant component

of landings for small-scale fisheries in the Mexican Caribbean (Rivera-Garibay and others, 2024). Regional variations in the impacts of plastic pollution are likely and may disproportionately affect small-scale fisheries, although evidence on this relationship is incomplete.

Small-scale fisheries are overlooked in the climate change literature and in assessments by the Intergovernmental Panel on Climate Change (IPCC) (Villasante and others, 2022). However, the projected effects of climate change (IPCC, 2023) will have a disproportionate impact on small-scale fishing communities, with varying levels of intensity in different regions associated with shifts in sea surface temperature, range shifts and stock composition change, sea-level rise, changes in rainfall patterns, shifts in salinity associated with saltwater intrusion from higher levels of freshwater inflow, an increase in extreme weather events and associated coastal erosion, ocean acidification and coral reef bleaching (Bell and others, 2013; Mimura, 1999; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019, 2024). Abnormally warm water temperatures and other climate stressors directly affect the quantity and the quality of small-scale fisheries' catch (FAO, Duke University and WorldFish, 2023), with correlated socioeconomic impacts for thousands of vulnerable households. The total maximum catch potential in the world's exclusive economic zones (EEZs) is likely to decrease by 7% to 12% by 2050 if a "business-as-usual" greenhouse gas emission scenario is followed, strongly driven by changes in plankton productivity (Monnier and others, 2020). The decrease could be up to 40% in some areas of the intertropical zone, largely affecting countries that are most dependent on fisheries as a source of protein (Monnier and others, 2020). Small-scale fisheries are likely to suffer the most significant impacts from these climate-driven changes, compounded by the effects of increasing industrialization, urbanization and the multiple uses of aquatic spaces (FAO, Duke University and WorldFish, 2023; Berkes and Franz, 2025).

Competition with other fisheries sectors, including IUU fishing, generates a range of pressures and impacts. For instance, it is well established that competition and conflicts with industrial fishing boats are a major threat to small-scale fishing livelihoods in some regions (Horta and Defeo, 2012; Okafor-Yarwood and others, 2022; Seto and others, 2023) (see subsect. 5A, subchap. 1A). Many countries have pursued the expansion of industrial fisheries as a development strategy for decades (Ayilu and others, 2023; Schuhbauer and others, 2019). This has intensified the overexploitation of resources and increased pressure on small-scale fishing, leading to significant levels of inequity and evidence of conflict between small-scale and industrial fisheries (Crona and others, 2021; Seto and others, 2023). Small-scale fisheries frequently compete for market share with products from industrial fisheries, aquaculture and imports (Crona and others, 2016; Pita and others, 2020), posing a range of livelihood challenges. Furthermore, IUU fishing, piracy and unsustainable fishing practices are closely connected to a lack of enforcement and limited public involvement in management (Widjaja and others, 2023). IUU fishing is a major threat to marine ecosystems and fishery resources and can lead to the significant loss of local fisheries, with small-scale fisheries in developing countries known to be particularly vulnerable (FAO, 2024; Song and others, 2020; WIOMSA, 2022). However, assessments of the impacts of IUU on small-scale fisheries are complicated by the various forms and drivers of IUU, the role of small-scale fisheries in IUU and the lack of consensus on what constitutes IUU in some regions (WIOMSA, 2022; FAO, 2024). Regional variation complicates the development of guidelines to address IUU and common monitoring indicators (FAO, 2024).

Globally, the impact of maritime safety interventions and security policies, often in tandem with blue economy strategies, is established but incomplete. In West Africa, for example, security zones are being imposed around sensitive maritime areas (e.g. offshore hydrocarbon infrastructure) (Adjei and Overå, 2019; Beseng, 2019). Artisanal fishers may be detained or harassed if they enter these areas. A ban on fishing within 500 m of oil rigs similarly limits the activities of artisanal fishers in Ghana and Nigeria and reduces access to traditional fishing grounds (Okafor-Yarwood and others, 2022; Bell and others, 2021), thus requiring them to go further out to sea, with concomitant safety risks.

Disruptions to sea lines of communication through acts of piracy and armed robbery in strategic regions, such as the Gulf of Aden, the Gulf of Guinea, the South China Sea and the Red Sea, further limit freedom of navigation for small-scale fishers (Liss, 2014; Bell and others, 2021; Guilfoyle, 2013). Numerous Security Council resolutions on piracy and armed robbery at sea have been adopted with the aim of mitigating these dangers. At the national level, anti-piracy measures may include prohibitions on small-scale fishers using certain harbours, the imposition of curfews (Bell and others, 2021) and no-fishing zones. An increased law enforcement presence at sea

may reduce piracy and armed robbery, but results in the loss of traditional fishing grounds or restricts access to fishing areas at specific times for fishers, often without compensation (Bell and others, 2021). In some situations, small-scale fishers are mistaken for pirates and either reported as suspicious (mostly in the Gulf of Guinea) or targeted, as in the Southern Indian Ocean. Many artisanal fishers operate at night (Mills and others, 2014), leading to further uncertainty and livelihood impacts.

Marine conservation policies and specific interventions, such as marine protected areas (MPAs), can contribute to the sustainability of small-scale fisheries (e.g. spillover effects) and the protection of habitats and species at specific life stages. There is evidence that well-managed MPAs may result in "co-benefits" for fisheries and coastal communities (Ban and others, 2019; Nowakowski and others, 2023; Costello, 2024). However, increased efforts to achieve the "30 by 30" targets of the Kunming-Montreal Global Biodiversity Framework may exacerbate the challenges faced by small-scale fisheries. More than 190 countries committed to the target of protecting at least 30% of terrestrial and inland water areas and marine and coastal areas by 2030 (Eckert and others, 2023). Contemporary marine conservation efforts can marginalize coastal and small-scale fishing communities (Cinti and others, 2024; Tafon and others, 2022) through the implementation of fishing bans and no-take zones, enclosure and access constraints, or top-down enforcement of conservation regulations (Muhl and others, 2020; Trimble and others, 2014; Bennett and others, 2021b; Ertör, 2023). In South Africa, for example, conservation efforts have displaced small-scale fishing communities from historically important fishing areas (Peer and others, 2022; Sowman and Sunde, 2018). Such initiatives can further alienate the underresearched, and largely undocumented, cultural fisheries management strategies for funerals or chiefly investiture of Indigenous Peoples and local communities, resulting in further displacement and exclusion (Vave, 2022). Negative impacts include the loss of community harvesting in conservation zones for funerary feasts and the loss of Indigenous Peoples' and local communities' cultural practices, which can affect access rights and identity (Vave, 2022).

3. Social components

Along the fish value chain (i.e. harvest/capture, processing and marketing), small-scale capture fisheries provide full- or part-time employment opportunities for approximately 60.2 million people, or about 90% of the total number of people employed in capture fisheries globally (FAO, Duke University and WorldFish, 2023; FAO, 2024). As of 2016, when the latest projections were available, close to 500 million people were estimated to depend in some way on small-scale fisheries for their livelihood, with an estimated 53 million people directly involved in fishing for subsistence (i.e. primarily for family food needs (FAO, 2024)). Notably, the FAO technical guidelines for responsible fishing place an emphasis on fish processing, trade and poor-friendly market systems to enhance economic efficiency and welfare gains in developing countries (Bjorndal and others, 2014; Pradhan and others, 2022).

Key social attributes influence the distribution of economic and livelihood benefits within small-scale fishing communities, including gender and identity (Galappaththi and others, 2022), displacement and labour precarity (Marschke and others, 2019), security/safety at sea (Guilfoyle, 2013), social protection (FAO, 2019; Tabe-Ojong and others, 2025) and well-being (Trimble and Johnson, 2013; Weeratunge and others, 2014). Efforts to build socially viable small-scale fisheries must engage more fully with fishers' place-based knowledge (Kitolelei and others, 2021; Pascua and others, 2017). A focus on value chains also enables a coherent assessment of equity and the distribution of benefits. There is evidence of traders and processors accessing exclusive market information that facilitates exploitative social relationships and constrains the power of small-scale fishers (Ferrol-Schulte and others, 2014; Pradhan and others, 2022).

The financial viability of small-scale fisheries is influenced by other sectors and actors, including informal finance providers, such as fish buyers or gear suppliers, through high-interest loans and unfavourable repayment structures, including selling catches when market prices are at their lowest (Kleih and others, 2013; Okafor-Yarwood and others, 2024a). Fish buyers provide de facto controls on the amount and price of small-scale fishery catches, serving as a driver for overexploitation (Kamiyama and others, 2015). There is limited reporting on the specific terms and conditions imposed by such fund providers. Informal financing of small-scale fisheries is common because formal banks are reluctant to

lend money to perceived high-risk or unstable borrowers, including small-scale fisheries (Jimenez and others, 2020). In many cases, opportunities to upgrade small-scale fisheries are structured by social relationships and local embeddedness (Adhuri and others, 2016).

The gender dimensions of small-scale fisheries are significant (see subsect. 5B, chap. 6). An estimated 53 million people are directly involved in fishing for subsistence; 39.6% of those engaged in the small-scale fisheries value chain through direct employment or subsistence fishing are women (FAO, Duke University and WorldFish, 2023). Close to 50% of post-harvest workers are women (FAO, Duke University and WorldFish, 2023). Compared with other industries, small-scale fisheries significantly contribute to gender equality (Harper and others, 2020; Kleiber and others, 2017). Women and men perform complementary roles: men are primarily involved in marine capture fisheries, while women focus on processing, trade and marketing (Pedroza-Gutiérrez and Hapke, 2022).

Globally, women catch approximately 2.9 million (+/- 835,000) tons of fish and invertebrates annually, with an estimated landed value of $5.6 billion (Harper and others, 2020; FAO, Duke University and WorldFish, 2023). This accounts for 12% of the total landed value of small-scale fishery catches and generates an overall economic impact of $14.8 billion annually (+/- $4 billion) (Harper and others, 2020). Women may also have prominent leadership roles in all aspects of a fishery, including management and governance (Chambon and others, 2024; Galappaththi and others, 2022). However, women tend to have more unstable positions within fishery value chains despite their roles (Eurostat, 2023; Chambon and others, 2024). Women in small-scale fisheries are also subjected to wage inequalities (Aini, 2022), domestic and/or workplace violence (Mangubhai and others, 2023) and limited acknowledgement of their work, which is often viewed as an extension of their household responsibility (United Nations Entity for Gender Equality and the Empowerment of Women (UN-Women), 2020). Opportunities to enhance environmental and human well-being outcomes require ongoing efforts to address gender inequities across the small-scale fisheries value chain (Cohen and others, 2024).

Small-scale fisheries are increasingly characterized by precarious working conditions, including extreme weather events, and labour relations that can undermine the significant contributions of small-scale fishers (Marschke and Vandergeest, 2016; Belton and others, 2019; Cruz-Del Rosario and Rigg, 2019). Furthermore, in developing countries, small-scale fisheries may lack social protection programmes or receive limited support to mitigate vulnerabilities (Tabe-Ojong and others, 2025). Small-scale fishers are often forced to fish further from shore for longer periods of time, particularly given general decline in stocks. Workers in small-scale fisheries rarely have contracts, work long hours, are often paid on share of the catch, based on how much fish is caught, and fish seasonally. Depending on the context, boat ownership can be next to impossible in some coastal communities, resulting in some fishers migrating for work elsewhere. For example, former Cambodian small-scale fisher households can be found in Thailand working in pre-processing (women) and as fish workers (men) on crab boats. In Indonesia, small-scale fishers migrate for work, with men separated from their families for years at a time. Investments around labour protection, individual and collective control and decent work are critical for such fisheries (Marschke and Vandergeest, 2016; Bavinck and others, 2024; Lozano and others, 2022).

Small-scale fishers, including Indigenous small-scale fishers, are keen stewards of their environments, reflecting patterns of change and seasonal variability (Galappaththi and others, 2021) (see subsect. 5B, chap. 8). A systems-oriented understanding of their environment emerges from the accumulation of shared knowledge over generations within communities, often transmitted orally (Galappaththi and Schlingmann, 2023; Silvano and others, 2023). The importance of paying greater attention to knowledge systems is reflected in evidence that aquatic food dependence among coastal Indigenous Peoples worldwide is much higher than it is among non-Indigenous peoples (Cisneros-Montemayor and others, 2016). This dependence was greatly affected by the coronavirus disease (COVID-19) pandemic and was addressed through barter exchanges for goods such as dried fish (Nhiwatiwa and Matanzima, 2023) (see subsect. 5B, chap. 7). In West Africa, responses to the pandemic highlighted the level of resilience in small-scale fishing communities, where fishers were forced to innovate in light of limited support (Okafor-Yarwood and others, 2022). In other global assessments, there is a reluctance to draw on fisher knowledge and observations (Ford and others, 2016).

4. Governance

Small-scale fisheries are complex socioecological systems (Charles, 2023; Berkes and Franz, 2025), requiring governance approaches that are collaborative, adaptive and multilevel (see sect. 3). Governance of small-scale fisheries also requires transparency, accountability and a focus on equity (see subsect. 5B, chap. 5). Globally, small-scale fishers and partner civil society organizations have a long history of documenting inequities associated with coastal development policies. Policies that have an impact on small-scale fisheries should seek more inclusive outcomes aligned with the Sustainable Development Goals.[1] The Ocean, Water and Fisher Peoples' Tribunals under the World Forum of Fisher Peoples are an example of forums of justice being established to give voice to testimonies and experiences of human rights abuses faced by fishing communities. In addition, independent people's tribunals on the implications of the blue economy were held in at least six countries around the Indian Ocean and in Brazil (Satizábal and others, 2024). Similar initiatives have emerged in Latin America and the Caribbean and elsewhere (Gerhardinger and others, 2023; García-Lorenzo and others, 2024).

At the global level, the *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* (FAO, 2015) represent the first international policy instrument entirely dedicated to small-scale fisheries. However, experiences implementing the Guidelines in different jurisdictions have been ad hoc (Chuenpagdee and others, 2017; Said and Chuenpagdee, 2019). There is established but incomplete evidence that key obstacles to the full implementation of the Guidelines include incoherence with existing national policies and requirements for national Governments to adapt or adjust existing regulatory frameworks (Cohen and others, 2017). Efforts to increase policy coherence with the Guidelines are being supported through the development of national plans of action for small-scale fisheries, with support from FAO.

The implementation of the Voluntary Guidelines is a pathway to achieving the Sustainable Development Goals of the 2030 Agenda. Small-scale fisheries are explicitly addressed in target 14b of Goal 14, on life below water: provide access for small-scale artisanal fishers to marine resources and markets. However, preferential access for small-scale fisheries globally is very low (Said and Chuenpagdee, 2019). Aligning their policy frameworks at the local, subnational and national levels with the Goals and the Guidelines provides a foundation for multilevel interventions (Smallhorn-West and others, 2022). With reference to small-scale fisheries, particularly Indigenous People's fisheries, attention is increasingly being paid to human rights-based approaches (FAO, 2015), including links between small-scale fisheries and rights to food security (FAO, 2015). The basis for a human rights-based approach is expressed in the United Nations Declaration on the Rights of Indigenous Peoples of 2007 and the United Nations Declaration on the Rights of Peasants and Other People Working in Rural Areas of 2018. Other global governance dialogues and multilateral environmental agreements will increasingly affect small-scale fisheries (see sect. 3), as reflected in the findings and evidence provided by IPBES assessments or in the emerging global plastics treaty.

At the national and subnational levels, evidence that the co-management and participatory governance of small-scale fisheries yield more equitable outcomes is well established, although strongly context-dependent (d'Armengol and others, 2018; Evans and others, 2023; Ruano-Chamorro and others, 2023). Success requires the active involvement of fishers and diverse stakeholders, strong government support, sustainable financial resources and transparent and adaptive decision-making processes (d'Armengol and others, 2018; Livingstone and Anthony, 2023). The Voluntary Guidelines and several international and national policy instruments already advocate for the increased participation of men and women in decision-making processes. Co-management, involving small-scale fisheries, Governments and other stakeholders, is now widely considered a best practice governance approach (Prado and others, 2022; Smallhorn-West and others, 2022). The most frequent goal of co-management is to improve fisheries management through increased participation, increased legitimacy and/or compliance with fishing rules, the definition or enforcement of fishing rights and the incorporation of customary management norms into formal management (d'Armengol and others, 2018). Evidence showing that co-management leads directly to better ecological outcomes is unresolved.

Evidence in support of the co-management and participatory governance of small-scale fisheries is often aligned

[1] See www.ssfcalltoaction.org.

with recognition of tenure. The Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security (FAO, 2022) clearly articulate the importance of tenure in regulating how societies make decisions about who can use which resources, for how long and under what conditions, including rights of decision-making. Effective and equitable governance of tenure is a critical variable in small-scale fishery outcomes, including for biodiversity (Cohen and others, 2024; Tholan and others, 2024). Groups with secure tenure can advance cost-effective management strategies. Secure tenure also makes it more likely that activities along the small-scale fisheries value chain will be compliant with international protocols and achieve positive environmental outcomes (IPBES, 2022a, 2022b). Secure governance of tenure for small-scale fisheries must extend to land for storing boats and gear, as well as post-harvest activities, including space to sort or dry fish, and also allow related economic activities such as marketing and selling (FAO, 2024). Despite a recognition of tenure implications, regional experience shows that the governance of tenure for small-scale fisheries in many jurisdictions is under threat from various forms of development – such as infrastructure and industrial aquaculture – as well as conservation pressures (Okafor-Yarwood and others, 2022; Cohen and others, 2019). There is evidence of arbitrary evictions and conflict in many small-scale fisheries contexts despite legal and policy frameworks established to limit such situations (FAO, 2015; Courtney and Jhaveri, 2017). Secure systems of tenure established through customary law and/or Indigenous systems of governance are particularly vulnerable. Loss of tenure can undermine the sense of place and area-specific knowledge of small-scale fishers (Bavinck and Gupta, 2014).

The availability of data and information on diverse small-scale fisheries activities and catch levels remains an ongoing governance issue, amplified further by the wide range of targeted species (Pita and others, 2019). There are also regional and national variations in how data-poor fisheries are defined, although some basic criteria provide a foundation for the development of monitoring programmes (Dowling and others, 2015). Fishers themselves provide valuable data and information on fisheries stocks, trends, harvest pressures and livelihood/food security implications, which can counter perceptions about data-poor small-scale fisheries (Gill and others, 2019). To enhance governance of these fisheries, ongoing efforts are required to improve low-cost methodologies that provide access to a wide range of social and ecological knowledge to overcome data-poor situations (Pita and others, 2019).

Data-poor fisheries are linked in part to compliance and traceability concerns in the small-scale fisheries sector, including IUU fisheries. Compliance at the individual fisher level remains poorly understood (Battista and others, 2018). Perceptions of legitimacy, fairness and equitability of rules play a key role in compliance, and are mediated by social norms and collective obligations. The participation of small-scale fishers in developing and applying rules has a significant effect on compliance (FAO, 2024). The role of technology in improving data collection for marine management is worth acknowledging, while noting the vulnerability of some small-scale fisheries to targeted monitoring. For example, in West and Central Africa, the close proximity of small-scale fishers to the shore and their visibility to law enforcement personnel make them an easy surveillance and enforcement target (Okafor-Yarwood and others, 2024c; Paes and Okafor-Yarwood, 2024), and may restrict their activities compared with the monitoring measures applied in the industrial sector (Okafor-Yarwood and others, 2022).

The value of ecosystem-based fisheries management to support governance is increasingly well established. The implementation of ecosystem approaches, such as the ecosystem approach to fisheries, over the past decade has helped to reorient management objectives and establish new methods that are relevant to data-limited contexts (Zhang and others, 2011; Link and Brown, 2017) (see chap. 27 of the second *World Ocean Assessment*). Integrated fisheries risk analysis methods for ecosystem approaches (Zhang and others, 2009, 2011) explicitly consider the status of local fish stocks, habitats, biodiversity measures and economic indicators for fisheries (see chap. 25 of the second *Assessment*). Ecosystem approaches have recently been applied in several small-scale fisheries, such as Egyptian fisheries in the Red Sea (Alsolami and others, 2020), local fisheries on the south coast of the Republic of Korea (Kang and Zhang, 2023) and fisheries in Indonesian waters (Tirtadanu and others, 2024). Efforts to improve traceability and certification are also aimed at increasing transparency in value chain governance and adherence to sustainable harvesting norms. However, global eco-label standards in general remain expensive, struggle to include social sustainability criteria and, most importantly, have not effectively included small-scale fisheries (Purcell and others, 2018; Bailey and others, 2016). Similar governance mechanisms such as fair trade certification have a stronger emphasis on

repositioning and empowering producers by mandating fair pricing standards. A growing number of local and national certification and labelling schemes for small-scale fisheries are emerging (e.g. Abalobi in South Africa and Pesca de Rias in Spain). However, certification processes are not fully developed in small-scale fisheries contexts and are rarely focused on ecological sustainability dimensions (Purcell, 2017).

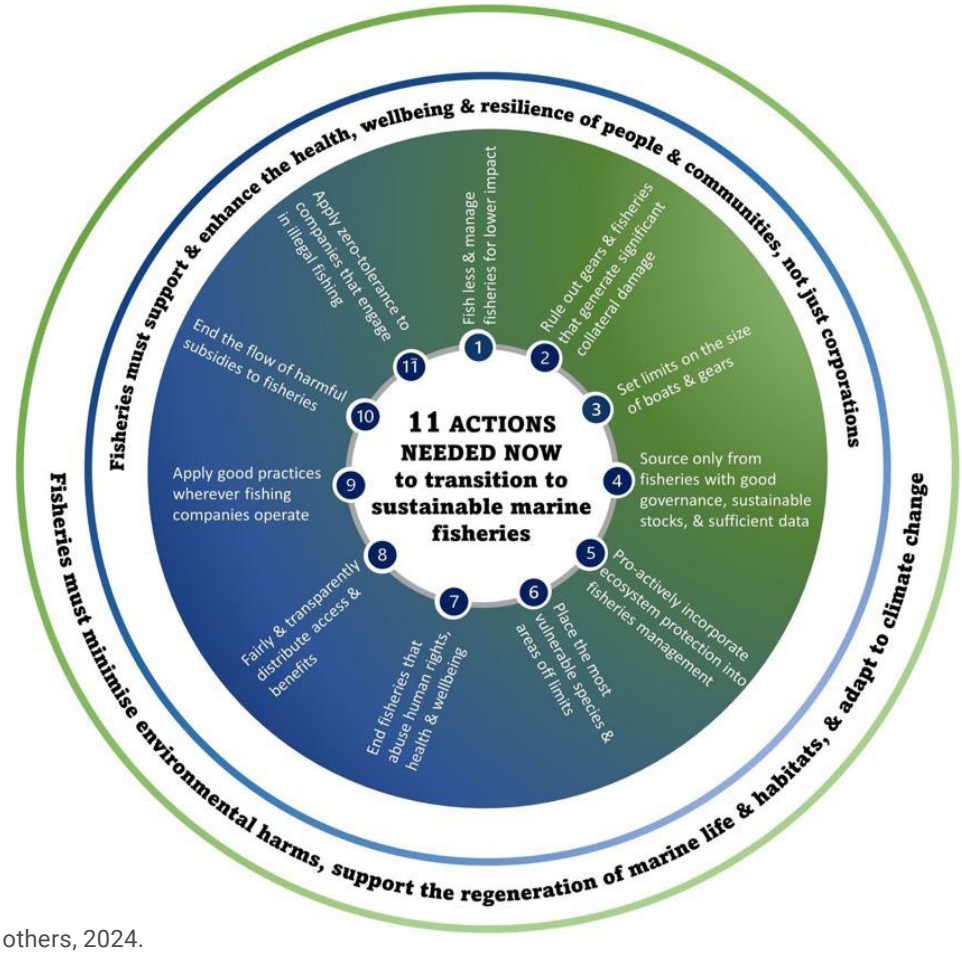
5. Sustainable pathways

The FAO *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* outline diverse pathways to help to secure sustainable small-scale fisheries. Efforts to amplify and extend these pathways must be centred on the calls to action from small-scale fishers themselves and the Coalition for Fair Fisheries Arrangements (CFFA) "Rules of conduct for working with small-scale fishers and fishworkers" (CFFA, 2023). Indeed, small-scale fisheries are a crucial economic sector, employ millions of people, support food security for millions more and exhibit significant resilience despite numerous challenges (Basurto and others, 2025; Berkes and Franz, 2025).

Transition pathways for sustainable small-scale fisheries that build on the Guidelines and are aligned with the Oceans 2050 scenario are emerging but incomplete.

Roberts and others (2024) provide a road map for fisheries reform and 11 actions to transition to sustainable marine fisheries, most of which are of direct relevance to small-scale fisheries (see figure II). The *Illuminating Hidden Harvests* report (FAO, Duke University and WorldFish, 2023) outlines several pathways to secure the role of small-scale fisheries in sustainable development, including acting on existing policy commitments and improving how fisheries data and information are collected, analysed and used.

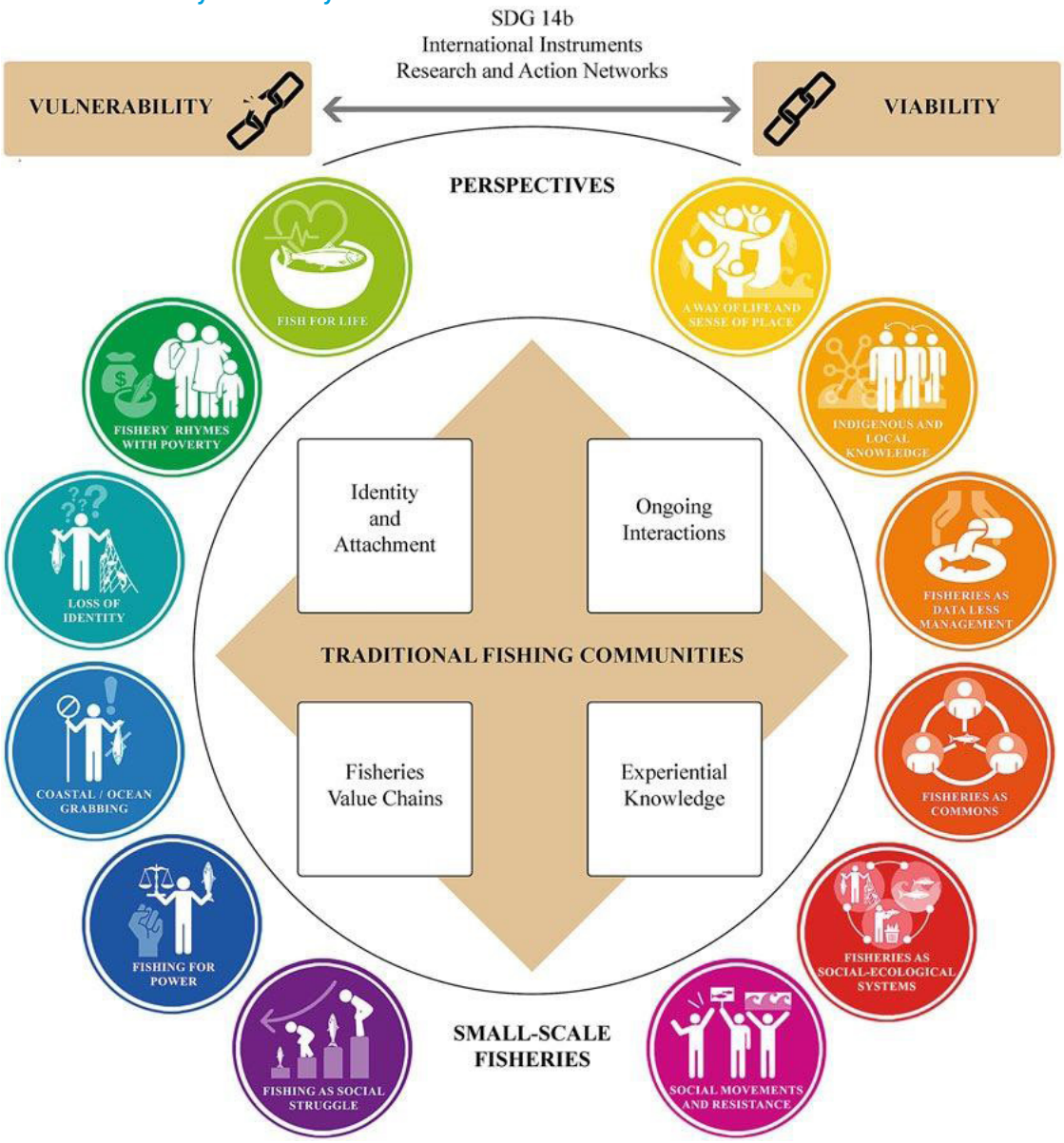
Figure II
Road map and actions to transition to sustainable marine fisheries



Source: Roberts and others, 2024.

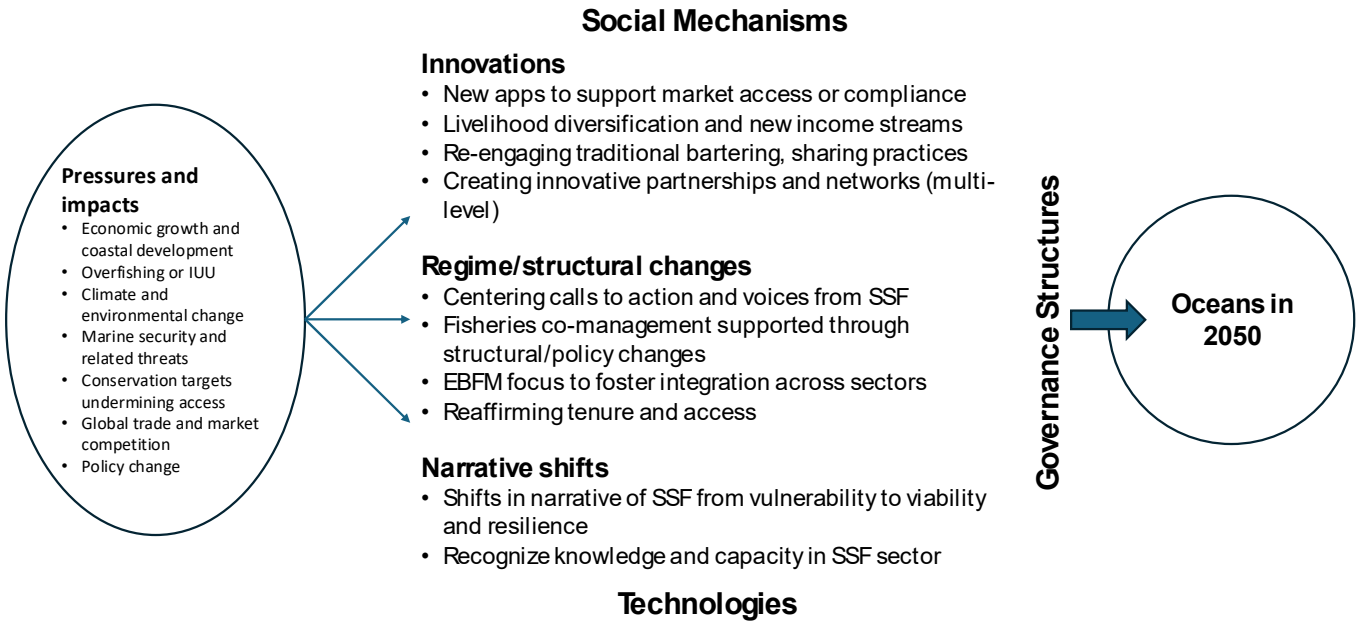
Nayak and others (2021) outline a variety of domains and perspectives around which the vulnerability, viability and sustainable development transitions of small-scale fisheries can be navigated, with an emphasis on social struggles and contested arrangements of power (see figure III). Muhl and others (forthcoming) document five key transition pathways from vulnerability to viability for small-scale fisheries based on experiences in 12 countries in Africa and Asia, including building governance networks and partnerships, centring small-scale fisheries' tenure and rights, advancing a gender and intersectional perspective on viability pathways, enhancing opportunities for nature-based livelihoods and co-creating or co-producing the knowledge needed for transition pathways. A range of other empirical analyses and policy assessments further articulate elements of transition or transformation pathways for small-scale fisheries (see Saunders and others, 2016; Salgueiro-Otero and others, 2022; Villasante and others, 2022; Gianelli and others, 2024; Berkes and Franz, 2025). The transition pathways outlined in the present subchapter build on existing assessments, but with specific consideration of the Oceans 2050 scenario. Emphasis is placed on the innovations, structural/regime changes and narrative shifts needed to catalyse the technological, governance and socioeconomic dimensions of sustainable pathways (see figure IV).

Figure III
Transitions from vulnerability to viability



Source: Nayak and others, 2021.

Figure IV
Sustainable pathways for small-scale fisheries under the Oceans 2050 scenario



Source: Prepared by the writing team.

Social and economic mechanisms for sustainable pathways to the Oceans 2050 scenario are diverse and will vary across the value chain. Participation, collaboration and mutual support, partnerships and networks of small-scale fisheries are core features of any successful transition pathway. Pathways must also reflect a commitment to the principles of equity and justice, drawing connections to human rights and security, including labour, safety and security of access (Reis-Filho and others, 2024). The significant knowledge and capacity of small-scale fisheries to lead transitions must be emphasized, along with a commitment to principles and practices of knowledge co-production (Mills and others, 2022; Muhl and others, 2023). Furthermore, pathways for sustainable small-scale fisheries must reflect the strong connections within and across sectors (for example, the links between small-scale and industrial fisheries through IUU and trawling practices are significant). More generally, a core principle in considering sustainable pathways is recognition of the deep relationship between small-scale fishery practices, socioeconomic prosperity (e.g. food security and employment) and ecological systems (Charles, 2023).

Providing stronger financial and economic support to small-scale fisheries is necessary to catalyse innovative practices, such as creating new markets, or diversifying or augmenting livelihoods. Several measures, such as savings groups, microfinance or insurance schemes, have been introduced to change the relationship between fishers and informal financial providers (i.e. fish buyers or gear suppliers) (Pomeroy and others, 2020). These interventions face challenges given the complex, long-standing social relationships in small local communities, but they help to shift the narrative of small-scale fisheries as vulnerable. Savings groups organized by local communities provide innovative pathways for such fisheries in Cambodia, the United Republic of Tanzania and other jurisdictions (Lieng and others, 2018; Nakamura and others, 2024). Advancing local, bottom-up initiatives, assisted by outside resources, is one pathway to disentangle the complex problems associated with informal finance providers, particularly at the harvest and marketing stages of the value chain (Pradhan and others, 2022). Furthermore, additional financial support is needed to ensure that individuals and small-scale fisheries organizations can engage with the growth of digitalization and e-commerce in the marketplace. An important social sustainability pathway also includes communities retaining and supporting traditional practices of bartering goods and services in lieu of monetary payments – a process that re-emerged during the COVID-19 pandemic (Nhiwatiwa and Matanzima, 2023). Traditional or customary practices serve as an important safety net since small-scale fishery incomes are typically low, may be the sole income contribution to households and/or support extended multigenerational families.

Governance processes related to small-scale fisheries for an Oceans 2050 scenario must be adaptive, collaborative

and multilevel. They must also be transparent and inclusive and support more decentralized and/or bottom-up decision-making processes. The implementation of the 2030 Agenda requires management grounded in a socioecological systems approach in order to achieve the integrated set of global priorities and objectives set out in the Sustainable Development Goals (see chap. 27 of the second *World Ocean Assessment*), which provide a foundation for the Oceans 2050 scenario. There are still gaps in implementation and incomplete uptake across regions and stakeholders. Common frameworks and criteria for small-scale fisheries governance based on demonstrated best practices are necessary.

Governance changes are aligned with technological tools and opportunities. Advances in technology enable small-scale fisheries to play an active role in fisheries governance and co-management systems – a crucial pathway for sustainability. In Liberia, for example, "Dase App", a smartphone application developed and maintained by the Environmental Justice Foundation, has been used by local fishers as part of the co-management process to collect data on possible IUU fishing infractions by trawlers. The mobile app enables users to capture video or photo evidence of destructive IUU fishing in real time, regardless of their Internet connection. However, its effectiveness is contingent upon the training of fishers on safe use and the willingness of government departments to take appropriate action when possible infractions are reported (see Livingstone and Anthony, 2023).

Pathways to sustainability will require further investments in governance and technological innovations and transfers applied at scale, with the aim of supporting market access, security and management by fishers. Technology uptake in the service of small-scale fisheries requires system-level changes and a shift away from narratives that such fisheries are risk-averse or disconnected from other related sectors. In particular, technology changes are closely linked to issues of access (i.e. access to knowledge, markets, credit and resources/space) that catalyse sustainable pathways.

6. Conclusions

Small-scale fisheries are highly variable and also distinct from other fisheries. They are of significant social, economic, cultural and ecological importance and play a crucial role in fostering food and nutritional security for millions of people (Basurto and others, 2025). Yet they face progressively significant pressures from many stressors, and their viability in many regions is increasingly threatened. Sustainable pathways for small-scale fisheries must be guided by the knowledge of fishers and, among other things, their active participation in decision-making. Their governance should be guided by principles of equity, justice and human rights. Furthermore, sustainable pathways must reflect the deep integration of the small-scale fisheries sector in a range of national and global governance processes, economic development policies and conservation agendas. There is a clear opportunity for Governments to support the knowledge, practices and capacity of small-scale fisheries and to recognize their crucial role in meeting the global Sustainable Development Goals.

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Subchapter 1C
Medium- and large-scale aquaculture

Key points

- Digitalization and emerging technologies are playing increasingly important roles in many different parts of aquaculture production.
- Social acceptability issues are emerging in species that were previously accepted, such as molluscs.
- Future development requires meaningful engagement with local communities when planning and managing aquaculture.
- Across all topics there is a need for more detailed and disaggregated data to allow more informed assessments at the local, national and international levels.
- Climate change will bring new challenges throughout the aquaculture value chain, and increased attention needs to be given to climate change adaptation and mitigation.

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1. Introduction

Over the past two decades, aquaculture production has increased at a rapid pace, and the sector has become more integrated within the global food system (Naylor and others, 2021). During this time, there have been many changes in farming methods as well as major developments throughout aquaculture value chains, with aquaculture products now among the most globalized food items (Ababouch and others, 2023). Marine aquaculture is a major component of the global aquaculture sector (Food and Agriculture Organization of the United Nations (FAO), 2024b) and an important contributor to food and nutrition security, supplying essential fatty acids, vital nutrients and desirable foods, often with lower environmental impacts than other forms of animal protein production (Tigchelaar and others, 2022). In 2023, the General Assembly adopted resolution 78/69 entitled "Oceans and the law of the sea", in which it noted the need for actions to support sustainable fisheries and sustainable aquaculture for sufficient, safe and nutritious food, recognizing the central role of healthy oceans in resilient food systems and for achieving the 2030 Agenda for Sustainable Development (United Nations General Assembly, 2023). As part of the ocean and climate change dialogue under the United Nations Framework Convention on Climate Change, it is recommended that national climate policies be linked with blue food production (Cordano and O'Dea, 2023). This emphasis underscores the importance of sustainable marine aquaculture in global food production both now and in the future.

Previous World Ocean Assessments had a single chapter dedicated to aquaculture but in the present *Assessment* aquaculture has been divided into a subchapter on small-scale aquaculture (subect. 5A, subchap. 1D) and the present subchapter on medium- and large-scale aquaculture. There are no formal definitions for distinguishing between small-, medium- and large-scale aquaculture: "scale" can refer to a range of production, technological, economic, social and environmental considerations and contexts (Krause and others, 2020). In the present *Assessment*, medium- and large-scale aquaculture refers to commercially oriented production for domestic or export markets, conducted by companies ranging from medium-scale enterprises to large-scale multinational companies. The focus is primarily on sea-based production, such as fish cages or longlines for seaweed and shellfish, as it is directly linked to the ocean, although land-based systems that interact with the marine environment (e.g. seawater use or effluent discharge), including coastal ponds and recirculating aquaculture systems, are also included where relevant. Although sea-based production still relies on more traditional technology, there are other emerging technologies (Føre and others, 2022), including closed and semi-closed containment (Nilsen and others, 2020), submerged production (Sievers and others, 2022) and aquaculture vessels (Long and others, 2024).

There are gaps and discrepancies in how aquaculture data are collected and reported (Kebede and others, 2024). Data sets rarely distinguish between small-, medium- and large-scale aquaculture, and marine production is not easily disaggregated from general aquaculture statistics that also include freshwater and brackish water data. Nevertheless, data from FAO provide an overview of the aquaculture sector (FAO, 2024a, 2024b). According to records classed as marine environment records in the "Global aquaculture production 1950 – 2022" data set in the FAO fishery and aquaculture data platform, marine aquaculture production increased from 55.7 million tons to 60.2 million tons between 2018 and 2022, and the overall value rose from $76 billion to $89.2 billion (FAO, 2024a). There is no noticeable impact on total production from the coronavirus disease (COVID-19) pandemic (FAO, 2024b), but on a finer scale, the actual consequences of the pandemic were more complex, with challenges for some companies but opportunities for others (Nielsen and others, 2023).

The aim of the present subchapter is to provide an overview of the current status of medium- and large-scale marine aquaculture and put forward a vision for the future. The first three parts of the subchapter (on pressures and impacts, socioeconomic aspects and governance) are focused on the assessment period for the third *World Ocean Assessment*, covering the years 2018 to 2023. The final part (on sustainability pathways) considers what future decades up to 2050 could look like under a business-as-usual scenario and identifies potential actions for a more sustainable future.

2. Pressures and impacts

Most medium- and large-scale aquaculture takes place within a few kilometres of the coastline (Papageorgiou and others, 2021; McIntosh and others, 2022; Liu and others, 2023; Harvey and others, 2024), but new technologies, industry expansion and intensification are changing how aquaculture utilizes ocean space (Bjelland and others, 2024; Buck and others, 2024), and changes are not homogeneous around the world. In China, according to estimates, the area used for marine aquaculture in 2020 was almost three times greater than in 2010 (Liu and others, 2023). In the Mediterranean, however, over a similar period, the total number of cages increased only very slightly, but the number of small cages decreased, and there was an increase in the number of medium and large cages (Papageorgiou and others, 2021). In many areas, coastal space is becoming increasingly scarce (Sanchez-Jerez and others, 2016) and conflict with other marine users has been highlighted as a constraint to further the development and expansion of marine aquaculture (Galparsoro and others, 2020). Marine spatial planning and zoning are frequently promoted to manage conflict over space and resources, but the lack of data, insufficient tools and poor governance are barriers in some locations.

Climate change also brings challenges for aquaculture production and the wider supply chain (Stavrakidis-Zachou and others, 2021; Fuentes-Santos and others, 2021; Falconer and others, 2022; Kim and others, 2024). Over the assessment period, there are examples of studies describing climate-related events affecting marine aquaculture, including marine heatwaves in the Mediterranean (Atalah and others, 2024), harmful algal blooms in Chile (Soto and others, 2021), storms in Viet Nam (Pham Thai and others, 2023) and typhoons in China (Li and others, 2024; Yin and others, 2024). Since the frequency and intensity of climate stressors are projected to increase over the next decades (Intergovernmental Panel on Climate Change (IPCC), 2023), there will be implications for future planning of the sector. There is increasing emphasis on the need for aquaculture companies to monitor their own contributions to climate change and implement mitigation measures throughout the entire value chain to reduce emissions (Jones and others, 2022). Studies have shown that feed production (MacLeod and others, 2020) and transport to market (Ziegler and others, 2024) are among the highest contributors to greenhouse gas emissions. Knowing where emissions occur along the value chain will allow the sector to act. Ziegler and others (2024), for example, estimated a 10% reduction in farmgate emissions for 1 kg of Norwegian salmon between 2017 and 2021 due to changes in feed ingredients.

Since the publication of the second *World Ocean Assessment*, increased attention has been given to low-trophic marine species, including large-scale farming of molluscs and seaweed. Low-trophic farming is one of the oldest types of aquaculture and is a large contributor to total production (FAO, 2024a, 2024b), but the renewed focus promotes further expansion to meet demands for sustainable food production (Krause and others, 2022). However, it is also recognized that there are many challenges that need to be addressed if large-scale low-trophic aquaculture is to significantly increase, especially as some parts of the world have been experiencing stagnation or declines in the production of low-trophic species (Avdelas and others, 2021; Botta and others, 2020). One of the main barriers in many areas is the availability of farming locations that can provide sufficient resources to sustain large-scale production over many years. In the case of mussels, challenges with wild seed supply have been reported in Spain (Padin and others, 2024), New Zealand (Skelton and others, 2022) and Chile (Molinet and others, 2021). At present, mussel hatcheries are unable to meet the demands of the sector as they are too small-scale, not cost-effective or not permitted by the authorities (Avdelas and others, 2021; South and others, 2022). Trials are under way to improve the efficiency of collectors (van Broekhoven and others, 2024) and increase seed retention using management techniques (Reyden and others, 2024). In Chile, mussel collectors seem to be extremely efficient, although there are concerns about the potential impact of overfishing of larvae (Molinet and others, 2021).

For fed aquaculture (e.g. fishes and shrimps), concerns remain over the use of marine ingredients (fishmeal and fish oil), the overexploitation of wild stocks (Colombo and others, 2023; Eroldoğan and others, 2023) and feed-food competition (van Riel and others, 2023) (see subect. 5A, subchap. 1A). Over the past three decades, there has been a significant reduction in the proportion of marine ingredients in aquaculture feeds, particularly salmon feed (Aas and others, 2022). Since the publication of the second *World Ocean Assessment*, despite considerable research and development efforts, there have been no major breakthroughs. Research is focusing on alternative ingredients such as insect meal, single

cell proteins and microalgae (Colombo and others, 2023; Glencross and others, 2024) but in 2020 only 0.4% of salmon feed ingredients were from such sources (Aas and others, 2022). The use of alternative ingredients is very likely to increase in future years for salmon and other species (Albrektsen and others, 2022; Colombo and others, 2023), but there are many factors that will affect the rate at which it will happen, and this field of research is very dynamic since feed is a major expense during the farming cycle (Iversen and others, 2020).

Over the assessment period, the use of digitalization and precision fish farming techniques increased (Føre and others, 2018, 2024) in order to optimize feeding practices (for example, Georgopoulou and others, 2024), helping to reduce environmental impacts (Mustapha and others, 2021). For traditional cages, the collection of waste remains challenging and is rare in commercial settings due to the volume of waste and the depths involved. Waste collection is likely to be more feasible in semi-closed or closed containment systems (Schumann and Brinker, 2020; Føre and others, 2022), as well as in recirculating aquaculture systems (Sánchez and Checa, 2023), although most of these systems are still in their infancy and not a significant part of commercial-scale production. Integrated multi-trophic aquaculture, in which non-fed species such as bivalves and seaweed utilize the waste from fed species like finfish, has also been identified as a potential route to increase production and reduce environmental impacts, but there are limited examples of commercial-scale integrated multi-trophic aquaculture farms due to planning, regulatory and operational barriers (Stenton-Dozey and others, 2021; Sickander and Filgueira, 2022). However, there is potential for a more regional approach to integrated multi-trophic aquaculture and for landscape-scale or water body-scale integration (Sanz-Lazaro and Sanchez-Jerez, 2020), as seen in Chile, where large-scale salmon farming occurs in the same areas in which intensive mussel farming takes place (Camelo-Guarín and others, 2021).

During the assessment period, considerable attention has been given to antimicrobials and to the potential for antimicrobial resistance due to its implications for human health (Reverter and others, 2020; Schar and others, 2020; European Food Safety Authority and others, 2024). In 2015, States Members of the United Nations committed to producing national action plans for antimicrobial resistance and, by 2020, many of the major aquaculture-producing States had included aquaculture within such plans (Caputo and others, 2023). Significant efforts over the past decade have been focused on reducing antimicrobial dependency in aquaculture (Bondad-Reantaso and others, 2023). Alternative prevention and therapeutic strategies have been developed, including vaccination (Barnes and others, 2022), functional feeds and phage therapy, a natural, targeted biocontrol method using species-specific bacteriophages (viruses of bacteria) to treat bacterial infections, offering an alternative to antibiotics (Kalatzis and others, 2018). However, these methods face challenges in large-scale adoption due to high development costs and strict regulatory requirements. Therefore, although some countries are seeing a decline in antimicrobial use, usage is increasing in others (Lulijwa and others, 2020). Further work is needed to achieve the recommendations and standards set by international organizations and certification schemes (Luthman and others, 2024), and a critical issue is the need for more reliable data, particularly in the shrimp sector (Thornber and others, 2020).

Escapes from farms are a concern, as they represent an economic loss to producers and can also have adverse ecological impacts, such as interbreeding with wild populations and spreading disease to wild populations (Sawayama and others, 2019; Atalah and Sanchez-Jerez, 2020). It is difficult to determine the status of aquaculture escapes since many countries do not have formal reporting requirements, and surveillance schemes are often inadequate or absent (Soto and others, 2023; Toledo-Guedes and others, 2024). In the Mediterranean, escapes of Gilthead seabream (*Sparus aurata*) have been significantly correlated with seabream landings from fishing vessels, suggesting that escapes contribute to this type of fishery (Toledo-Guedes and others, 2024). In some locations, there have been reductions in the number of escapes. For example, over the past two decades there has been a significant effort in Norway to reduce escapes through strict regulations and technical standards (Afewerki and others, 2023), and recent estimates suggest that about 0.04% of Norwegian farmed salmon are registered as escapes (Føre and Thorvaldsen, 2021). In Norway, there have also been considerable efforts to develop and use triploid salmon that are sterile and unable to reproduce, but there are challenges in their use (de Fonseka and others, 2022), and in 2023, due to welfare concerns, the Government of Norway announced that it would not allow the use of triploid salmon in food fish

production.[1] Escape concerns are often greater where non-native species are used (Soto and others, 2023), as escaped species can become invasive, outcompeting local species and affecting ecosystem structure and functioning. A recent worldwide assessment revealed that approximately 26% of marine fish production involves species that are not native to their marine ecoregion (Atalah and Sanchez-Jerez, 2020).

3. Socioeconomic aspects

Compared with the years covered by the first and second World Ocean Assessments, the period from 2018 to 2023 saw a lot more attention paid to aquaculture in the media (Condie and others, 2022; Machado and others, 2023; Sutherland and Armbrecht, 2024). Negative media articles were focused on salmon production and its environmental effects more than on any other species. In some cases, previous high-profile events, such as environmental problems in Macquarie Harbour in Tasmania, Australia, leading to an increased public focus on environmental sustainability and governance, caused this uptick (Condie and others, 2022). Mainstream media tended to be more negative in developed countries than in developing countries (Budhathoki and others, 2024). Local settings influence the portrayal, limiting the ability to make generalizations; for example, in New Zealand, it has been suggested that the tendency towards negative media portrayals occurs as the industry reaches maturity (Condie and others, 2022), whereas in Atlantic Canada social acceptability increased with the age of the industry (Kraly and others, 2022).

Strongly linked to changing public perceptions of aquaculture, in the period 2018–2023 (and starting in the years just preceding), the concept of a social licence to operate became firmly embedded in societal discussions on commercial aquaculture, as well as being evident in government policy and industry strategy (Alexander, 2022). Efforts to explore the use of social licences to operate for aquaculture products has primarily been focused on salmon (e.g. Weitzman and others, 2023; Eriksen and Mikkelsen, 2024; Olsen and others, 2024) and seaweed (e.g. Billing and others, 2021; Rostan and others, 2022). A key finding across these studies is that social licences to operate are local in nature, and the need for efforts to secure and maintain such licences should be adapted to the local context.

The importance of understanding the broader social impacts of aquaculture is also coming to the fore and includes aspects such as the consideration of livelihoods and human development, human rights, social and cultural needs, flow-on economic benefits and improved infrastructure, among other issues (Alexander and Kelling, 2024). However, data are lacking in relation to many of these aspects (Krause and others, 2020; Mikkelsen and others, 2021), making it difficult to assess what has changed in the 2018–2023 period. What is known is that social and human concerns are insufficiently addressed in the aquaculture sector (Brugere and others, 2023). An example is the increasing awareness of the need to address gender equality in the aquaculture sector (see also subsect. 5B, chap. 6), aligning with the Sustainable Development Goals (Troell and others, 2023), but assessment of gender-related issues in the aquaculture sector is difficult due to the lack of gender-disaggregated data (Kruijssen and others, 2018; Gopal and others, 2020; Brugere and others, 2023; Troell and others, 2023). Nevertheless, research has shown that female practitioners in the aquaculture industry chain face issues related to worker safety and unequal pay, as well as constraining gender norms and discrimination (Rao and others, 2024).

Data suggest that aquaculture employment may have decreased slightly globally during the period under review, although the picture on a regional basis shows significant increases in Latin America and the Caribbean and a decrease in Asia (FAO, 2024b). In Europe, Northern America and Oceania, which are primarily focused on large-scale commercial aquaculture, employment figures have remained stable. The traditional skills required for employment in the sector are not easily transferable as new technologies such as sensors, big data, machine learning and artificial intelligence have become more prominent (McDonald and others, 2024). It is not clear if this digital capability training was under way between 2018 and 2023, although during this period the European Union launched the "Blue careers for a sustainable blue economy" programme aimed at developing the next generation of blue skills for sustainable maritime careers (European Commission, 2022).

The social considerations associated with aquaculture also extend to working conditions. Globally, several

[1] See www.regjeringen.no/no/dokumenter/meld.-st.-8-20242025/id3080297.

occupational health and safety problems are prevalent among aquaculture workers, including ergonomic hazards, musculoskeletal complaints, diseases and injuries (Fry and others, 2019; Kaustell and others, 2019; Mitchell and Lystad, 2019; Moreau and Neis, 2009; Myers, 2010; Ngajilo and Jeebhay, 2019; Watterson and others, 2020). Norwegian studies of salmon farming have found that employees worry about strain and injuries and that organizational challenges related to goal conflicts, work pressure and employee participation can be found (Kongsvik and others, 2018; Thorvaldsen and others, 2020). As the mitigation of these risks has received little attention globally, researchers have called for a global commitment for occupational health and safety in aquaculture (Cavalli and others, 2019). Working conditions for aquaculture workers were also a topic at the sixth International Fishing Industry Safety and Health Conference, held in January 2024, which was aimed at helping to advance safety and health research and increase awareness of safety and health issues in fishing, aquaculture and seafood processing (Lincoln and others, 2024). Sadly, human rights abuses can be found everywhere, but during the period 2018–2023, issues faced in the aquaculture sector increasingly became an issue, with certification schemes particularly being challenged by third-sector organizations such as charities and non-profit organizations (see, for example, Human Rights at Sea, 2023). Making the headlines, a 2024 report, based on data collection commencing in 2021, detailed pervasive systematic abuse throughout the Indian supply chain, including the exploitation of vulnerable workers, forced labour and dangerous conditions (Corporate Accountability Lab, 2024).

Over the assessment period, increased attention was given to sustainable food production and the societal benefits of different food types. With increasingly stringent constraints on terrestrial land use driven by climate change and biodiversity conservation, a well-managed ocean is poised to become a primary source of food to meet humanity's growing demand, and marine aquaculture will account for most of this growth (Costello and others, 2020). Seafood provides the most dominant source of omega-3 long-chain polyunsaturated fatty acids and holds significant potential to reduce micronutrient deficiencies (Golden and others, 2021). In addition, many forms of marine aquaculture have a smaller environmental footprint than industrial meat production, especially red meat, which has significantly higher resource demands (Gephart and others, 2021). There are also calls to recognize the range of purposes that aquaculture can have beyond food production (Mizuta and others, 2023). For example, the rise of stock enhancement aquaculture has aided in the recovery of some wild fish populations, as evidenced by the initial success of large yellow croaker population recovery in Chinese coastal waters (Yuan and others, 2021). Furthermore, ocean-reliant communities worldwide are facing increasing pressures to shift their livelihoods, and marine aquaculture provides a reliable alternative livelihood source (Gentry and others, 2020). Low-barrier entry aquaculture practices enable persons in marginalized situations, often women, who previously lacked access to means of production, to directly participate in production, thereby improving gender equality (McClenachan and Moulton, 2022; Wurmann and others, 2022).

4. Governance

Aquaculture governance is paramount to securing sustainable production and industry, but has been implemented in different ways across the globe (Naylor and others, 2023), with public regulation ranging from being starkly absent to highly present. Public governance of aquaculture requires scientifically founded regulation that is adaptable and flexible in relation to the type of aquaculture present and its development, capable of nurturing the abilities of the private sector, public regulators and non-governmental organizations (NGOs) alike, and in a manner that supports control, transparency and accountability (Ababouch and others, 2023). FAO guidelines for assessing legal frameworks for aquaculture support such an approach while identifying the necessary regulatory mechanisms for advancing sustainable aquaculture (Hodgson, 2023). Between 2016 and 2018, Galparsoro and others (2020) conducted a large-scale global stakeholder consultation to identify the major obstacles preventing the development and expansion of marine aquaculture, and found that almost 40% of the responses were related to administrative challenges, including licensing and regulation. A literature review also found that complicated and fragmented approaches to planning and licensing were frequently highlighted as barriers for marine aquaculture expansion (Falconer and others, 2023). Studies have also emphasized that many existing regulatory frameworks may not be suitable for new technologies, alternative locations or innovative

production methods, including farming in more exposed or offshore waters (Davies and others, 2019; Watson and others, 2022; Krause and others, 2024).

Since the publication of the second *World Ocean Assessment*, there have been examples of proactive governance initiatives to encourage responsible aquaculture development at the national and international levels. A notable international development was the adoption of the Guidelines for Sustainable Aquaculture in 2024 (FAO, 2025), a framework aimed at helping States Members of the United Nations and stakeholders to develop and intensify aquaculture sustainably. The guidelines were prepared by FAO and are aligned with the 2030 Agenda for Sustainable Development and the relevant Sustainable Development Goals (United Nations General Assembly, 2015), as well as other key policies and agreements. At a more regional scale, the FAO General Fisheries Commission for the Mediterranean (GFCM) has taken significant steps to support the Mediterranean and Black Sea aquaculture sector. The Commission's 2030 Strategy (FAO, 2021), which is aligned with the Sustainable Development Goals, envisions a sustainable, resilient and fully realized sector. As Mediterranean aquaculture-producing countries generally adhere to a vertically integrated system of legal requirements established at the national, European Union, subregional and Mediterranean levels (Papageorgiou and others, 2021), the Commission plays a crucial role in guiding this sector. Effective governance is encouraged through enhanced collaboration with the Commission's contracting parties and cooperating non-contracting parties (FAO GFCM, 2025) alongside stakeholders, to create supportive legal and administrative frameworks. Ensuring sustainability also depends on effective spatial planning, embracing digitalization – namely the integration of digital technologies, data analytics and automation (Internet of Things, sensors, artificial intelligence, remote monitoring systems and big data analytics) – to support data-driven decisions, and promoting diversification towards a lower environmental impact. Knowledge-sharing is facilitated through dedicated demonstration centres, and the creation of technical advisory groups under different thematics, such as animal health and welfare or innovation and technology, is enabling the involvement of experts and the dissemination of actions.

During the assessment period, there were several notable actions within the salmon farming sector that could affect where and how salmon are produced, including changes in tax regimes (Misund and others, 2024) and regulatory restrictions in some locations (Mather, 2024). Such interventions have been driven by a complex interplay of rights holders and stakeholders in the management of aquaculture and balancing environmental concerns and socioeconomic impacts. Since these are recent developments, the consequences are inconclusive at present. Alongside national regulation, private certification schemes have emerged as a response to the perceived inefficiency of public regulation, mainly for securing transparency in and access to a global market. Certification schemes act as a mechanism to increase transparency and accountability across different producers. Recent years have seen the number of schemes increase in parallel with an expansion of potential applications and increased uptake. The Aquaculture Stewardship Council is an example of a certification scheme. Globally the number of farms certified by the Council almost tripled during the reporting period, from 800 in 2018 to 2,085 in 2023, and there is reason to believe that other schemes have also increased in use. However, data on the proliferation of most schemes are not made public, and comparisons are difficult across schemes as the entity certified ranges from production sites to entire companies. Schemes may serve as decision-making information to investors, politicians and public authorities, as risk-reducing mechanisms for retailers, or as a filter distinguishing between sustainable and unsustainable choices for consumers, and they provide access to markets and price premiums for producers (Bush and others, 2013; Bush and Oosterveer, 2015; Olsen and others, 2021; Tlusty, 2012). Topics relevant for various schemes are food safety risks, the degree of sustainability, fish welfare practices, working conditions, transparency and many others. However, the specific definitions of sustainability as promoted by different schemes are often strongly skewed towards environmental topics and food safety, and less towards socioeconomic sustainability (Osmundsen and others, 2020). Recently, schemes such as the Aquaculture Stewardship Council appear to be strengthening their standards in social and ethical domains.

The impact of certification on sustainability is hard to evaluate, but there is reason to believe that the development still follows the progress identified by Naylor and others (2021) in that environmental performance is improving as a response to increased regulation, including private certifications. Following the increased recognition of certifications, there is great variation in how assessments are carried out, ranging from desktop ratings on a narrow set of indicators to multiple on-site visits by professional auditors looking into every aspect of production. Some schemes intend to

give companies incentives to improve their practices and require improvements from audit to audit. While private certification schemes are often portrayed as voluntary mechanisms, they are de facto mandatory as purchasers and certain markets expect producers to comply with specific schemes, emerging as a corporate social responsibility strategy (Rector and others, 2024). The high number of labels and certification may cause confusion and label fatigue among consumers, thus weakening the effect of stimulating sustainable food choices. Other concerns relate to how certification may act as a barrier to trade for smaller companies or companies from developing countries that cannot afford the costs and documentation requirements (Bush and others, 2013). Certifications are often expensive to attain, and multiple certifications are required when targeting different markets (Amundsen and Osmundsen, 2020). Furthermore, global certification schemes catering for an international market may be disconnected from local sustainable practices and knowledge (Jolly and others, 2023; Little and others, 2018). The creation of standards that reflect the interests of consumers rather than local aquaculture production realities may shift focus away from practices that are sustainable in a local context.

5. Sustainability pathways

Medium- and large-scale marine aquaculture will play an increasingly important role in future food and nutrition security, so it is important to identify factors that support sustainable and responsible development and reduce negative impacts (Crona and others, 2023; Tigchelaar and others, 2022; Willett and others, 2019). Scenario analysis is a tool to identify pathways to a healthy and productive ocean in the future (Nash and others, 2022; Pecl and others, 2022), including aquaculture (Couture and others, 2021; Farmery and others, 2022). Here, scenario analysis is used to describe two potential pathways for medium- and large-scale marine aquaculture and link directly to the Sustainable Development Goals and contribute to a more sustainable ocean in 2050. The business-as-usual pathway describes a plausible future that is likely to occur based on current trends, in the absence of any major interventions or shocks. In contrast, the sustainable future pathway describes a more sustainable future that could occur with deliberate actions that change the current trajectory. Using information on the present status of medium- and large-scale aquaculture from the previous three parts of the present subchapter, together with information from the regional workshops held in preparation for the third *World Ocean Assessment*, two key drivers of change are identified: governance and regulation; and skills and capacity-building. The PESTLE (political, economic, societal, technological, legal, environmental) framework is then used to identify actions that could support the move to a more sustainable future (see table). The approach was adapted from the more comprehensive Future Seas 2030 project (Farmery and others, 2022; Nash and others, 2022; Pecl and others, 2022). These examples could be further developed by States Members of the United Nations and aquaculture stakeholders to create more detailed sustainability pathways using context-specific information.

Business-as-usual scenario

The industry continues to expand using existing farming methods as well as new technologies, novel production methods and new locations, contributing to achieving zero hunger (Sustainable Development Goal 2). Regulatory systems are improving but are still slow to reform compared with the pace of technological development, which limits overall production potential. Insufficient progress is made on environmental and social impacts across all forms of the production system due to reliance on outdated monitoring and assessment methods. While certification schemes start to move the industry towards more sustainable outcomes (Goal 12), they continue to be incremental and occur only in more sustainability-minded corporations. A lack of skills and capacity training leads to a decreasing and disillusioned workforce as traditional skills cannot be transferred to newer technologies and locations.

Sustainable future scenario

The industry continues to expand using existing farming methods as well as new technologies, novel production methods and new locations, contributing to achieving zero hunger (Goal 2). Significant financial investments in new and revised regulatory frameworks provide a more holistic and evidence-based approach to aquaculture licensing, increasing transparency in planning and management decisions for all stakeholders and the public. Environmental and social impacts are reduced due to innovative monitoring and revised approaches, which

consider the system holistically (addressing Goals 12, 13 and 14). Certification schemes push the sector above and beyond compliance requirements, leading to increasingly sustainable and responsible production (Goal 12). Government and industry-incentivized capacity-building schemes provide decent work opportunities that keep pace with industry development (Goal 8).

Below are some of the "governance and regulation" and "skills and capacity-building" actions suggested in the table that Member States could use to help move towards the sustainable future scenario. The ability to implement such initiatives, and the associated timescales, will depend on the aquaculture-specific context in each Member State.

Table

Potential actions for each driver of change that could accelerate progress towards a sustainable future scenario in which medium- and large-scale marine aquaculture contributes to increased production of high-quality protein in a responsible manner and supports decent work and economic growth

PESTLE category	Governance and regulation	Skills and capacity-building
Political	Produce novel governance frameworks that incentivize sustainable development, collaboration and transparency. Minimize potential conflicts of interests within government agencies, i.e. as promoter and regulator.	Establish and support initiatives that facilitate transdisciplinary co-production, sharing of knowledge and international cooperation related to new technology, novel production systems and governance.
Economic	Provide financial support to address bottlenecks in licensing and regulatory frameworks through streamlined administrative procedures. Financial support should also be used to update existing regulations or develop new licensing frameworks for novel farming systems. Improve collection and analysis of disaggregated economic data to support more informed assessments and improvements in governance and regulation.	Allocate financial support for capacity-building and skills training throughout the industry and associated activities. Include schemes that will enable upskilling and retraining in new technologies and novel production systems. Improve collection and analysis of disaggregated workforce data to support targeted financial support for capacity-building where required.
Societal	Co-develop marine spatial planning strategies with other activities, local stakeholders and communities to ensure trust, procedural fairness and redistribution of profits. Enable processes that minimize conflicts with other ocean users. Promote aquaculture literacy. Improve the collection and analysis of disaggregated social data, including better data on gender, to support more informed assessments and improvements in governance and regulation.	Increase awareness of the roles, experience and skills required in aquaculture, e.g. precision farming. Ensure that training programmes emphasize occupational health and safety. Provide accessible career mentoring schemes for new entrants, returners and the long-term workforce.
Technological	Incentivize novel and improved farming systems, particularly in new areas, e.g. the open ocean, that optimize species health and welfare, are safe for workers and reduce negative effects on the environment.	Create infrastructure to support capacity-building and skills training. Enhance collaborative opportunities for data collection, analysis and sharing to inform decision-making. Strengthen access to educational resources such as digital content. Support hatcheries and breeding programmes.
Legal	Revise licensing and regulatory frameworks to address bottlenecks based on evidence, ensuring that regulations are adjusted to fit the scale and risk of the farming operation. Develop and revise legal frameworks for novel farming systems. Provide legal mechanisms to co-develop marine spatial planning strategies with other activities, local stakeholders and communities.	If required, develop enabling legislation to support relevant infrastructure to support capacity-building. Develop training schemes to support the implementation of health and safety regulation. Ensure that cross-sectoral training schemes align with regulatory requirements for marine spatial planning.
Environmental	Promote environmental data collection and analysis, including climate change modelling, to enhance site selection to minimize antibiotic and chemical use and interactions with wild species (through escapes or diseases), and to reduce carbon dioxide (CO_2) emissions.	Organize exchange programmes that facilitate visits and placements across the aquaculture sector, including existing and new technology, for industry, researchers, policymakers, external stakeholders and wider society. Ensure that there are knowledge exchange opportunities with other sectors to improve marine spatial planning.

Source: Prepared by the writing team.

Governance and regulation

A sustainable future relies on governance and regulatory frameworks that have strong social credentials, generated through greater trust and transparency among all actors and a better understanding of how aquaculture operates within the environment and overall societal contributions. Ocean literacy has been defined as a catalyst that can accelerate systemic change and support sustainability goals (McKinley and others, 2023). In a similar way, aquaculture literacy could be a route to increased understanding of the role and responsibilities of aquaculture within the marine environment and how this links to other activities, which could then strengthen governance and regulatory frameworks. In Norway, several initiatives are aimed at increasing public knowledge of aquaculture, including visitor centres and a web-portal that includes facts, data and information for the general public (Mikkelsen and others, 2021).

Governance and regulation must be underpinned by scientific evidence as this increases legitimacy and trust in the rules and practices that are implemented. In this sense, the use of precision farming techniques (Føre and others, 2018) and large-scale monitoring, supported by remote-sensing and satellite data integration, will be crucial for predicting conditions not only in farms but also in aquaculture zones (Chatziantoniou and others, 2023), allowing better planning for aquaculture and better coordination with other activities, optimizing the use of space and resources, such as through marine spatial planning. In addition, increased dialogue and knowledge-sharing between sectors and marine users will lead to better understanding of requirements for marine space across all user groups to support the co-development of plans that reduce conflict. Digitalization of the aquaculture sector will support evidence-based co-development of spatial management plans and strategies with other activities and communities. Vast amounts of data collected at farms will provide greater insight into climate change for all marine activities (Falconer and others, 2025). Better understanding of the farming environment will allow for the development of adaptive management strategies, such as early warning systems and flexible farm designs, to increase resilience to climate change (Sanchez-Jerez and others, 2023). Where possible, climate adaptation measures should be mainstreamed into aquaculture planning and practices, especially in regions that are vulnerable to marine heatwaves and algal blooms.

Skills and capacity-building

The pressing need for increased amounts of responsibly produced food requires a significant boost in production at a rapid pace, which in turn demands a ready workforce equipped with the necessary knowledge, skills and experience. The aquaculture sector must consider new and innovative ways to attract new entrants and support the existing workforce in both reskilling and upskilling. Lifelong learning will be important for increased resilience in the future workforce, supported by fair and equitable access to new knowledge and training opportunities. Networking initiatives such as Women in Scottish Aquaculture could provide routes to mentoring and career support for new entrants, returners and the longer-term workforce (Kelling and Lawan, 2023).

Transformative change rarely occurs in silos, so actions are required that will support diverse and inclusive knowledge exchange and co-learning opportunities (Partelow and others, 2023). However, research infrastructure is expensive to install and maintain, which can exclude parts of the sector and limit the potential for upskilling or new knowledge generation. Within the research and innovation landscape, a European Union-funded project (AQUAEXCEL3.0, 2023) is an example of a mechanism that encourages new partnerships and widens access to research infrastructure that would otherwise be unavailable to many individuals and groups.

Aquaculture companies that intend to develop in more remote offshore locations will require more robust structures, advanced technologies and production systems with increased automation and reduced maintenance needs. There may be opportunities to cooperate with other sectors, sharing knowledge and research infrastructure. For example, the Government of Australia has partnered with industry and academia to establish the Blue Economy Cooperative Research Centre, a 10-year funded initiative that supports research and training initiatives across aquaculture, offshore engineering and renewable energy (Blue Economy Cooperative Research Centre, 2022).

6. Conclusion

Medium- and large-scale aquaculture is an important part of the ocean economy and an essential contributor to food and nutrition security. Since the publication of the second *World Ocean Assessment*, production has increased, but there are still bottlenecks and challenges that need to be addressed if the sector is to significantly increase production and contribute further to sustainability goals. Data gaps and the lack of consistent reporting across species, systems and locations are issues that make it difficult to understand the scale and importance of some topics. Nevertheless, across the sector there are many examples that show how innovative solutions have been used to address previous challenges.

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Subchapter 1D
Small-scale aquaculture

Key points

- Small-scale aquaculture in nearshore and coastal areas plays a significant role in global food security, livelihoods, nutrition and health, despite increasing threats from anthropogenic pollutants due to accelerating coastal population growth, which compromises ecosystem integrity that is essential for sustainable aquaculture operations in coastal waters.
- Some species and well-managed practices and systems have little or no negative impacts on ocean health (e.g. seaweeds and molluscs) and can provide significant ecosystem services by removing excess nutrients from ocean waters, thereby reducing pollution and enhancing carbon capture potential, leading to their classification as regenerative aquaculture.
- There appears to be a serious lack of specific national laws governing nearshore and coastal small-scale aquaculture sustainability. National laws and regulations need to be clear and promote the sector's growth within scientifically determined carrying capacities.
- It is time for States to provide greater attention, including on strengthening extension services, to nearshore and coastal small-scale aquaculture under their blue economy development programmes, which will collectively contribute to global food and nutrition security and to improving livelihoods while maintaining and improving ocean health.
- Considering the potential negative impacts of the aggregation of small-scale operations, spatial planning and addressing carrying capacity limitations should be encouraged at the national and regional levels.
- Best management practices, including biosecurity measures, should be implemented to protect small-scale nearshore and coastal aquaculture and make it more sustainable, with the least negative impacts on the ocean health.
- Improving multisectoral cooperation and communication between government agencies is crucial for enhancing marine aquaculture governance and ultimately improving ocean health.

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1. Introduction

The aquaculture industry produces over 500 species of aquatic animal and plant species destined for food and non-food purposes and operates at a range of scales (small, medium, large, commercial and industrial) in all aquatic environments (marine, brackish and freshwater). Since there is currently no single, globally accepted definition of "small-scale aquaculture", the term "small-scale" in the present subchapter is used for single or clustered (community-based) farming units operated by individual farmers, their families and/or groups of farmers, with minimum technology, inputs, services and resources. The subchapter is focused on small-scale aquaculture in two environments: (a) the nearshore marine environment (nearshore marine aquaculture, NSMA); and (b) the coastal environment (coastal marine aquaculture, CMA), typically in constructed ponds onshore or in intertidal zones. Both NSMA and CMA play a key role in providing livelihoods and employment, contributing to food and nutrition security and facilitating economic development among coastal communities in many countries, particularly in Asia and Latin America. Other scales of aquaculture (medium- and large-scale) are dealt with in subchapter 1C, while the culture of aquatic plants in the marine environment is discussed in the subchapters covering macroalgae and microalgae. Stocking and stock enhancement in marine waters are not discussed in the present subchapter, as they are considered fisheries activities.

In 2022, world aquaculture production, at all scales, reached a record 130.9 million tons, comprising 94.4 million tons (live weight equivalent; worth $295.7 billion) of aquatic animals and 36.5 million tons (wet weight; worth $17 billion) of algae (seaweeds and micro-algae), plus a further 2,700 tons (worth $138.5 million) of shells and pearls. While the production of farmed aquatic animals reached a total of 94.4 million tons, marine and coastal systems contributed a significant portion of this, alongside 36.5 million tons of algae (Food and Agriculture Organization of the United Nations (FAO), 2024a). Of the top 10 farmed aquatic species groups in the world, three are seaweeds, two are molluscs, three are freshwater fishes and one is a crustacean; several of the freshwater fishes can also be farmed in brackish waters. The top 10 marine and brackish water species groups are shown in table 1.

Information and disaggregated data on marine and coastal aquaculture production by scale are scarce. On a global scale, most small-scale global production of seaweeds, sea cucumbers and sea molluscs originate from NSMA, while crustacean production primarily takes place in onshore coastal brackish water ponds and tanks. In this case, CMA is dominated by brackish water shrimp and a few species of fish, crayfish and crabs. It is important to mention that coastal shrimp aquaculture in brackish water in Latin America is not considered small-scale.

Cage aquaculture (raising fish in enclosed cages) has been established successfully in nearshore and offshore marine areas. However, offshore marine cage aquaculture should not be considered small-scale. According to available information, cage culture in the sea contributes around 65% of the world's total production of finfish farmed in marine and coastal aquaculture combined (FAO, 2024a). However, the largest proportion (in biomass) involves large-scale offshore farming of salmonids, sea bream, seabass, tuna, cobia, etc. Most nearshore cage farms fall under NSMA.

The majority of NSMA consists of species that are found at the lower trophic levels, such as seaweeds and molluscs. There are a few exceptions, such as the green mud crab and prawns. However, the bulk of production comes from either non-fed (e.g. seaweed) or low-trophic-feeding species (e.g. mullets). Brackish water aquaculture is dominated globally by penaeid shrimp (see table 1).

According to FAO (2024a), aquaculture provided employment for approximately 22 million people globally in 2022 (95% in Asia), doubling the workforce from 1995 to 2016. However, there are no accurately disaggregated global data on employment in different environments and at different scales. Women play a significant role in small-scale fish and shrimp aquaculture, especially in the post-harvest segment of the value chain (in seaweed culture, women are greatly involved in the pre-harvest segment of the value chain), and although more women are involved in capture fisheries, the percentage of women is higher in aquaculture (Bartley, 2022). Again, no disaggregated data are available on women in NSMA and CMA.

Seaweed aquaculture holds significant social importance, balancing environmental health, economic growth and community well-being. As global demand for sustainable food and materials increases, seaweed cultivation offers a solution that is aligned with environmental stewardship and community livelihoods (Cottier-Cook and others, 2021).

From a socioeconomic perspective, seaweed cultivation provides job opportunities, particularly in coastal regions

in developing countries where traditional industries such as fishing may be in decline. It supports local economies by creating new markets for seaweed-based products, including food, cosmetics, biofuels and pharmaceuticals. This diversified income can help to alleviate poverty and improve community resilience to the impacts of climate change (Cottier-Cook and others, 2022). Seaweed cultivation also promotes food security and provides employment in many countries for women and marginalized communities (Asri and others, 2022; Msuya and others, 2022). The cultivation of seaweed also encourages sustainable practices in local communities, fostering environmental awareness and stewardship (Nagabhatla and others, 2023). While is it true that seaweed culture is not practised globally, the potential for its expansion and inclusion in efforts to increase food security, while improving ocean health, should be given due consideration.

Table 1
Top 10 marine and brackish water production, 2022 (Tons)

Marine species	Production
Japanese kelp (seaweed)	10 861 335
Eucheuma seaweeds	7 803 037
Cupped oysters	6 236 182
Ruditapse philippinarum	4 406 100
Gracilaria seaweeds	6 185 047
Wakame (seaweed) *Undaria pinatifida*	2 694 578
Atlantic salmon	2 867 856
Nori (seaweed)	2 176 580
Scallops	1 792 323
Brackish water and freshwater species	**Production**
Whiteleg shrimp	6 047 868
Gracilaria seaweeds	1 383 821
Milkfish	921 703
Nile tilapia	88 277
Giant tiger prawn	760 463
Freshwater fishes	279 455
Mullets	35 182
Marine fishes	291 819
Indo-Pacific swamp crab	96 388

Source: FAO, 2024b.

Aquatic animal foods are rich in protein and other nutrients, in particular long-chain omega-3 fatty acids and in various micronutrients and vitamins difficult to find in many other foods, such as vitamin A, iodine, selenium, calcium, iron and zinc. Seaweeds are also rich in nutrients, being considered among the healthiest foods, and their consumption is linked to improved public health outcomes (FAO, 2024a). In recent decades, significant growth in the aquaculture sector has contributed to the increase in global per capita consumption of aquatic animal food from 9.1 kg in 1961 to 20.6 kg in 2021 (FAO, 2024a), contributing to improved health and nutrition.

The growth rate of global aquaculture production (animals and plants) exceeds that of most other food production systems and still has immense potential for expansion. However, accurately quantifying the contribution of NSMA and CMA to community nutrition is challenging, considering the species cultured. However, the production of seaweeds, bivalves, crustaceans and finfishes in small-scale mariculture plays a significant role in local nutrition, since these products are often consumed in local markets in many countries. This is different from large-scale industrial aquaculture, in which products are mostly processed for export (e.g. Japan, United States of America, European Union) and/or for large national markets (e.g. China, Norway).

As in any other animal and plant production sectors, aquatic production is prone to disease (Ward and others, 2019). Global loss of revenue due to diseases in aquaculture is estimated to be over $10 billion annually (Kumar and others, 2024). Consequently, the use of antimicrobials in certain types of aquaculture has increased over the years. Although regulations governing the prudent use of antimicrobials are in place, there is evidence of increasing antimicrobial resistance globally (Schar and others, 2020).

Fish and shrimp aquaculture consumes significant volumes of marine resources (especially fishmeal and fish oil derived from pelagic marine fishes). As the demand for aquatic food and products is rising, it is important to expand and increase the production of non-fed, low-trophic species and better manage fed species production systems to safeguard ocean health. However, the harvesting of marine pelagic fishes has remained constant over the past few decades, while improvements in feed and feeding have allowed for tremendous growth in aquaculture.

In the present subchapter, issues of interest to maintaining ocean health linked to NSMA and CMA are discussed, along with opportunities for addressing them.

2. Pressures and impacts

World fisheries and aquaculture production of aquatic species is expected to grow to 205 million tons (live weight equivalent) by 2032. Much of the increase will come from aquaculture, which is expected to break the 100 million ton threshold for the first time in 2027 and reach 111 million tons in 2032 (FAO, 2024a). Considering the production trends during the past two decades, it is likely that NSMA and CMA will continue to expand in the next decade.

Extractive species of NSMA (species that obtain their feed directly from the sea and do not need external feeding) include molluscs and seaweeds. These farming systems typically cover a larger area than production systems involving fed species and their main interaction with the ocean is therefore not related to the individual impact of each small-scale farm, but to the aggregated cumulative impacts of many small-scale farms operating in one location (Harvey and others, 2024). The most relevant negative impacts of bivalve filter feeders are the deterioration of the seabed due to the accumulation of pseudofaeces (Marín and others, 2023). Although it has been demonstrated that organic matter can accumulate on the seabed beneath mollusc-farming areas, such accumulation depends largely on local hydrodynamics, inputs of nutrients from anthropogenic coastal sources and water properties such as salinity and temperature, as these parameters have been shown to be determinants of the capacity of mollusc farms to capture organic matter (Islam and others, 2024). Intensive bivalve farming can also lead to overharvesting of phytoplankton and changes to currents and water flow and light, among other things, that could affect the survival of other wild species (Harvey and others, 2024). The processing of farmed bivalve shells entails several environmental issues relating to terrestrial ecosystems around landfills, as well as to marine ecosystems due to the removal of calcium carbonate in shells. The burning of shells in landfills or for shell processing could also contribute to carbon dioxide (CO_2) emissions (Waldbusser and others, 2013; Gattuso and others, 2018, 2021; Hyun and others, 2024).

Some negative effects associated with seaweed farming have also been reported (Theuerkauf and others, 2019), relating mostly to modifications of currents, sediments and shading, but there are still many knowledge gaps (Fricke and others, 2024). In general, assessments of the impacts of molluscs and seaweeds at the global level are lacking, although some indicator assessments and standards for management are being proposed.

Some NSMA species, such as certain mussels, oysters and milkfish, involve the collection of wild seed, which can have negative impacts on ocean health (Byron and others, 2024). However, there is no accurate information on the maximum sustainable levels of extraction from the sea. Wild collection of post-larvae for CMA shrimp farming is almost non-existent.

In contrast, farming the above-mentioned species can generate important ecosystem services for humans and for the ocean ecosystem because they can filter out excess nutrients, thereby reducing human-induced ocean pollution (Barret and others, 2022) and increasing the ocean's potential to capture carbon. Chinese seaweed aquaculture, practised as NSMA, removes approximately 75,000 tons of nitrogen and 9,500 tons of phosphorus annually, and it is estimated that, with the current growth rate of seaweed aquaculture, seaweed farming could remove 100% of current phosphorus inputs to Chinese coastal waters by 2026 (Xiao and others, 2017). Thus, bivalve and seaweed farming are often considered under the category of "regenerative aquaculture" (Mizuta and others, 2023; Wong and others, 2024).

Small-scale shrimp aquaculture is developed in coastal marine areas that were often once covered by mangroves; the impact on coastal oceans should be related to the added effects of small coastal ponds. This practice is more prominent in Asia, while coastal shrimp farming in Latin America is a large-scale aquaculture activity. It is likely that the main impact on the ocean comes from the destruction of mangroves, which reduces their capacity for coastal carbon storage, and nutrient-filtering habitat provision for viable capture fisheries. Larger mangrove transformations into shrimp ponds will drain more nutrients into the sea. However, it is also evident that, at the global level, mangrove destruction is legally prohibited, and the regeneration of mangroves is promoted in many countries (Lecerf and others, 2023). Nevertheless, mangrove-friendly small-scale shrimp farming is practised in many countries (see figure).

Many NSMAs release plastic waste from floating systems, ropes and containers, among other things. Although it is not evaluated at a global level, NSMA can be a relevant source of microplastics and larger debris in the ocean in areas where debris is highly concentrated (Harvey and others, 2024). Small-scale farmers often lack adequate practices regarding the use and disposal of materials (Tian and others, 2022).

Figure
Small-scale shrimp farming in a mangrove area in Viet Nam



Source: Prepared by the writing team.

There is a need for better assessments of NSMA impacts and benefits for nearshore areas of the ocean. To improve the contribution of NSMA to ocean health, it is necessary to improve the spatial planning and arrangement of farms, as well as better manage individual farms. This can be done through stronger extension services and market incentives, such as area management certifications. However, it is important to bring the cost of certification down so that small-scale farmers could become partners of certification systems. This is necessary in order to change individual farmers' performance, since the implementation of better standards is often expensive and technically cumbersome.

Disease is one of the most important threats to sustainable aquaculture production, which is also of significant relevance to NSMA and CMA. Diseases in the marine environment affect both cultured and wild stocks and often pass undetected, undiagnosed, unreported and/or misdiagnosed, thereby hiding their true impacts. The direct and indirect costs associated with disease outbreaks in aquaculture thus tend to be underestimated (Subasinghe and Shinn, 2023). Although antimicrobial use in shrimp aquaculture has been significantly reduced, there are still allegations of irresponsible use in the sector. Nevertheless, in the CMA shrimp sector, the development of specific pathogen-free shrimp, along with controlled breeding in hatcheries, has not only reduced disease impacts and antimicrobial use in shrimp aquaculture (including small-scale producers), but also almost diminished the wild seed and broodstock collection (Alday-Sanz and others, 2018).

NSMA and CMA cannot be sustainable without addressing the impacts of climate change (CABI International, 2023). The major elements of climate change threatening NSMA and CMA production and sustainability include rising temperatures, ocean acidification, diseases, harmful algal blooms, changes in rainfall/precipitation patterns, sea-level rise, uncertainty about external input supplies, changes in sea-surface salinity and severe climatic events (CABI International, 2023). The potential impact is dependent on several factors such as the season, locations and size of the specific segment in the sector. Furthermore, communities engaged in NSMA and CMA are relatively poor, with limited resources, so their resilience to climate change is restricted in many countries.

Although some forms of aquaculture claim low greenhouse gas emissions and negative environmental impacts, the sustainability of aquaculture is widely debated. In 2000, a comprehensive review of the net contribution of aquaculture to world fish supplies was published in *Nature* (Naylor and others, 2000), portraying aquaculture in a very negative light in terms of its adverse environmental impacts. Later, in 2021, another article in *Nature* reviewed the developments in global aquaculture from 1997 to 2017, incorporating all industry subsectors and highlighting the integration of aquaculture in the global food system (Naylor and others, 2021). The review highlighted the major gains in aquaculture feed efficiency and fish nutrition, lowering the fish-in/fish-out ratio for all fed species, although the dependence on marine ingredients persists and reliance on terrestrial ingredients has increased. The review further recognized mollusc and seaweed culture for its ecosystem services; however, it admitted that the quantification, valuation and market development of these services remain rare. The authors concluded that the potential of molluscs and seaweed farming, which are most relevant to NSMA, to support global nutritional security is underexploited. Pressure on the aquaculture industry to embrace comprehensive sustainability measures from 1997 to 2017, however, has improved governance, technology, siting and management in many cases.

According to the International Marine Ingredients Organisation (IFFO), to sustain global aquatic animal production in 2020 (63 million tons), about 46 million tons of feed were used (IFFO, 2024). Based on projections by FAO, global aquaculture production is predicted to more than double, reaching yields of 140 million tons by 2050 (FAO, 2024a). This means that feed production needs to at least double to over 100 million tons during the same period. Among the fundamental questions underpinning that projection are how to obtain the feed ingredients to sustain such growth and how to ensure the sustainability of that growth (IFFO, 2024).

Fishmeal is one of the most important ingredients in livestock and aquaculture feed. About 18 million tons of fish are processed into fish oil and fishmeal for aquafeed, primarily marine pelagic fish. Although the El Niño Southern Oscillation and interdecadal variability have affected anchovy and sardine populations over time (Bertrand and others, 2020; Fang and Zhang, 2025), the production of fed fish for aquaculture (both marine and inland) has dramatically increased. Better farming practices and improvements in aquafeed formulations, such as the incorporation of alternative feed ingredients, have significantly reduced the amount of fishmeal and fish oil needed for most farmed fish species.

3. Sustainability pathways

Aquaculture and the environment

Although the assumption is that increasing food production will inevitably result in some degradation of nature, a convincing body of evidence is now available that challenges this assumption. In fact, it is possible to produce nutritious food and actively contribute to the recovery of ecosystems at the same time (The Nature Conservancy, 2023) through regenerative aquaculture (i.e. aquaculture that also provides ecosystem services, such as filtering water, sequestering carbon and providing habitat for other organisms). A recent report by The Nature Conservancy notes that the expansion of restorative aquaculture and improved management of wild fisheries could sustainably increase how much food is harvested from the ocean by 36% to 74% by 2050, making aquaculture a key part of transitioning towards a food system that works with nature (Bossio and others, 2021).

Aquaculture is recognized as one of the most environmentally efficient ways of producing food. This is especially true for bivalves and seaweeds. Recent research and assessments show that shellfish and seaweed farms, with the right practices, in the right places, can help to restore ocean health (Kuncoro and others, 2024), while supporting economic development and food production in coastal communities worldwide (Theuerkauf and others, 2019). A major step to increase the contribution of NSMA to food and nutrition is to enhance science and innovation efforts to increase seaweed use as direct food for humans.

Fulfilling aquaculture's growth potential requires responsible technologies and practices. Sustainable aquaculture should be ecologically efficient, product-diversified, profitable and societally beneficial, with acceptable levels of risk in terms of adverse environmental impacts. Integrated multi-trophic aquaculture has the potential to achieve these objectives by coupling non-fed NSMA farming (e.g. seaweeds, suspension and deposit feeders) to nearby farmed fed species (e.g. finfish-fed sustainable commercial diets), thus promoting the use of inorganic

and organic excess nutrients from fed aquaculture for the growth of the non-fed species. This approach, which is practised especially by NSMA communities, can help to improve the environment, the economy and social acceptability. This is being implemented in Chile by farming seaweed at industrial salmon farming sites when intensive aquaculture is in a fallow period.

Any production sector has an optimal environmental carrying capacity, beyond which the sector's sustainability becomes debatable. Applying cluster management approaches under the FAO ecosystem approach to aquaculture, which considers all the components of aquatic production within a specific geographic and social boundary, is aimed at integrating aquaculture with other sectors and ensuring that it contributes to social and economic development. Furthermore, as stated in chapter 25 of the second *World Ocean Assessment*, the ecosystem approach to aquaculture should be integrated with the ecosystem approach to fisheries to address the potential cumulative impacts of fisheries and aquaculture on coastal marine ecosystems (Kang and Zhang, 2021), which could be promoted by responsible aquaculture stakeholders with beneficial outcomes in coastal and nearshore aquaculture in many parts of the world.

Value chain and farming systems

Improving the sustainability of NSMA and CMA and reducing any negative impacts require a value chain approach. Strengthening the linkages between the different actors in the value chain will make it possible to address the constraints facing the actors and upgrade the value chain. Value chain analysis can highlight the role of governance in the value chain, that is, the structure of relationships and coordination mechanisms, linkages and trust that exist between actors, especially among the small-scale NSMA and CMA sectors. By focusing on these linkages, it is possible to identify the mechanisms that may need to be targeted to improve capabilities in the value chain, remedy distributional distortions and increase added value in the sector. There are examples of improved farming systems directly contributing to a reduction in the negative environmental impacts of coastal aquaculture, especially in small-scale shrimp aquaculture practices in Asia.

Climate

In comparison with livestock production, seafood production has lower carbon emissions. In addition, some species can extract carbon from aquatic environments, contributing to an extended carbon cycle. A recent review of the environmental consequences of aquaculture production and the potential effects of different aquatic products on greenhouse gas emissions suggested approaches for mitigating global climate change. They suggested improving feed efficiency, selecting suitable farmed species and implementing sustainable farming practices and management. Holistic evaluation and strategic intervention regarding greenhouse gas emissions are fundamental and essential for achieving a sustainable, low-carbon future for aquaculture (Zhang, 2024).

Seaweeds contribute to climate change mitigation through carbon capture via multiple pathways, with varying degrees of permanence. Through photosynthesis, seaweeds absorb dissolved inorganic carbon (DIC) from seawater and convert it to organic carbon compounds stored as biomass, dissolved organic carbon (DOC) and particulate organic carbon (POC) (Kim, 2024). While biomass storage is temporary unless harvested and processed, portions of DOC and POC can achieve long-term sequestration when transported to the deep ocean or buried in sediments (van den Burg and others; 2024; Kim, 2024; Fujita and others, 2022).

Current scientific evidence raises significant concerns about seaweed carbon sequestration, particularly regarding the practice of sinking seaweed biomass to the deep ocean, which could be potentially misleading (Chopin and others, 2024). The carbon stored in seaweed biomass likely represents temporary rather than permanent sequestration, with studies indicating that only 6% to 33% of theoretical CO_2 removal potential is achieved when accounting for air-sea CO_2 equilibration; deep-ocean dumping risks disrupting poorly understood marine ecosystems by smothering seafloor life, altering water chemistry and promoting deoxygenation; and complex transport pathways make verification and monitoring extremely difficult. While seaweeds do participate in carbon cycling through DOC and POC pathways, the scientific consensus emphasizes that seaweeds provide greater value when utilized for food security and other product value chains that deliver multiple ecosystem services, rather than being promoted primarily as carbon sequestration agents through deep-sea disposal, an approach that many scientists consider ecologically risky and a potential distraction from more effective climate solutions.

The sequestration efficiency of seaweeds also varies by species, cultivation method and environmental condition, with estimates suggesting a global potential of 61–268 teragrams of carbon annually, and on average

up to 173 teragrams of carbon per year, which in 2016 was about 11% of seaweed global net carbon production (Krause-Jensen and Duarte, 2016). Verification of CO_2 removal requires accounting for ocean-atmosphere CO_2 exchange dynamics and tracing carbon flows through marine systems (Hurd and others, 2022, 2024). The absence of rigorous carbon accounting methods precludes a conclusive assertion of the sequestration potential of seaweeds. While uncertainties remain regarding quantification and verification, particularly concerning air-sea CO_2 equilibrium time frames, the scientific consensus acknowledges the role of seaweeds in carbon sequestration as a legitimate area of research requiring further investigation rather than outright dismissal.

Climate-smart aquaculture is aimed at improving food security while considering the need to adapt and ways to reduce the effects of climate change (FAO, 2017). It tackles the difficulties of achieving synergies among the associated goals of mitigating climate change, adaptation and increased production and income, while reducing possible negative consequences. It is a useful strategy for reducing the potential impacts of NSMA and CMA on ocean health.

Genetic improvement

Genetic improvement of farmed aquatic species has been shown to improve several characteristics favourable to aquaculture, such as growth rate, body morphology and colour, fecundity, survivability and disease resistance. There are a range of genetic technologies available to aquaculturists (see table 2), although several of these technologies require resources, capacity and technology, which are not always available in NSMA and CMA. The domestication and genetic improvement of farmed aquatic species would reduce the negative impacts of aquaculture on the world's oceans and brackish waters. Atlantic salmon, Japanese kelp, oysters and white leg shrimp are notable examples of how genetic improvement can increase production and profits in aquaculture and reduce environmental impacts. While farming of Atlantic salmon is not included in NSMA, farming of white leg shrimp, oysters and Japanese kelp can be both intensive aquaculture and NSMA and CMA (Chen and Xiong, 2018). Among the best examples of genetic improvements in CMA that have significantly reduced the pressure on the ocean are specific pathogen-resistant and specific pathogen-free shrimp. The use of locally bred post-larvae by small-scale shrimp farmers under CMA has increased significantly over the past decade. Domesticated marine species would require less food, be more disease-resistant and have poorer survival in the wild in the event of escape. Unlike freshwater aquaculture, there are still challenges with the controlled breeding of several important farmed marine species, and therefore genetic improvement in marine species has not been utilized to the extent it has in freshwater species, making it an area of research requiring further attention. Marine species are also farmed for the ornamental pet fish industry. However, only about 2% of ornamental marine species come from aquaculture (Wabnitz and others, 2003). As most genetic improvements have been used by large-scale well-financed groups and usually not by small-scale aquaculturists, the challenge of the coming decade should be to make those relevant and proven genetic technologies and improvements available, assessable and affordable to small-scale aquaculture producers in NSMA and CMA, as has been done in freshwater species such as tilapia (Asian Development Bank (ADB), 2005). There is commercial potential for using DNA technologies to screen fish for diseases and make disease-free fish strains for NSMA, as has been done with shrimp farming in India (Thakur and others, 2013).

Non-native species

Non-native aquatic species introduced into new areas for fishing or aquaculture have been shown to increase production and profits. However, they have also been shown to pose threats, such as in establishing invasive species populations in both ecological and economic environments (Bartley and Halwart, 2006). Over 200 species are farmed in countries where they are not native; of the top 10 farmed aquatic species, 9 are more frequently farmed in countries where they are non-native than in countries where they are native (FAO, 2019). Although most of these are freshwater species (7 out of 10), the statistics demonstrate the economic value of non-native species in aquaculture. However, there are risks and, using freshwater data from the FAO Database on Introductions of Aquatic Species, more negative environmental impacts than positive economic impacts were reported for farming non-native species (Bartley and Funge-Smith, 2018), thus making risk assessment and the application of international guidelines necessary (International Council for the Exploration of the Sea (ICES), 2005).

Table 2
Genetic technologies: examples of genetically improved marine and brackish water species

Technology	Marine examples	Improvement
Short term		
Hybridization	Bester sturgeon (*Huso huso, Acipenser ruthenus*)	Improved growth rate; no need for diadromy
Chromosome set manipulation	Triploid Pacific oyster	Flesh quality; growth rate
Long term		
Selective breeding	Atlantic salmon/White leg shrimp	Growth rate; disease resistance; environmental tolerance
Gene transfer	Atlantic salmon	Growth rate; temperature tolerance

Source: Prepared by the writing team.

Feed

Based on the current growth of aquaculture, there is an urgent need to increase the production of aquafeeds. A crucial point is that they should not compete with the potential to feed humans. Several options have been proposed (Glencross and others, 2024), including: improving the management of existing resources to increase their productivity (option 1); ensuring that nothing is wasted, irrespective of the resources produced (option 2); and further developing non-competing resource production (option 3). However, the fishing of marine pelagics for rendering into feed provides a livelihood for many fishers, especially in Latin America, who would not otherwise have the resources to store and process their catch for human consumption (Wijkström, 2010).

In addition, there has been an increase in the use of by-products from fish processing plants in aquaculture feed to about 25–30%, thus reducing dependence on marine pelagic fish. Nonetheless, the aquaculture industry is looking for ways to reduce dependence on marine pelagic fish by including plant-based and insect alternatives. Soybean is the primary alternative to fish meal, but fish oil is harder to replace (Bartley, 2022). The use of algal oils has also been reported. Since formulated feeds are heavily used in the NSMA and CMA sectors, especially in coastal shrimp and nearshore fish culture, the application of better feeding practices and better management practices will further reduce the pressure on exploiting animal resources for aquaculture feeds from the ocean.

Disease

The need to increase aquatic food production while facing natural resource constraints will drive the intensification of aquaculture, thus inevitably enhancing disease risks in the sector. In past decades, there were major outbreaks of disease in NSMA and CMA. The progressive management pathway for aquatic biosecurity, introduced by FAO and supported by a variety of national biosecurity tools, is expected to play a major role in the systemic reduction of diseases and pests throughout the global aquaculture industry. It could significantly contribute to improving biosecurity in aquaculture, especially in the much-needed NSMA and CMA small-scale sectors, and lead to reduced environmental impacts, improved market access, increased smallholder income and the promotion of the One Health approach (FAO, 2023).

Governance

Aquaculture governance is the set of processes by which a jurisdiction manages its resources, how its stakeholders participate in making and implementing decisions affecting the sector, how government personnel are held accountable to the aquaculture community and other stakeholders, and how respect for the rule of law is applied and enforced. Good governance will ensure the sustainability of aquaculture growth and will help to reduce the sector's impacts on ocean health. Governance in aquaculture covers all sectors, environments and scales, including small-scale NSMA and CMA.

Aquaculture activities usually occur within national authorities, and the sector has traditionally been considered jointly with capture fisheries in policies and international agreements. Article 9, on aquaculture development, in the Code of Conduct on Responsible Fisheries provides governance advice to stakeholders, with special reference to the small-scale farming sector (FAO, 1995). Further guidance is provided in the recent FAO Guidelines for Sustainable Aquaculture (FAO, 2025). However, growing external pressures on the industry are prompting it to improve

its governance, and there is evidence of good practices in some parts of the world, which translate directly into high-production outputs. Achieving good governance in aquaculture is as important an objective as aquaculture development (increases in outputs) per se, as it will ensure the achievements of sustainable aquaculture development ecologically, economically and institutionally.

Most types of NSMA and CMA and their value chains are less organized and require assistance for improvement and further development in a more sustainable manner. In fact, it is hard for small-scale producers and value chain actors to comply with all of the sector's legal and governance regulations. Furthermore, an inability to comply with laws and regulations can make the small-scale aquaculture sector environmentally less sustainable, with the potential to create more negative impacts for production environments, and eventually for ocean health.

Improving governance of the small-scale aquaculture within NSMA and CMA will increase the overall sustainability and profitability of the sector. If not, the socioeconomic benefits of the sector will decline, requiring government interventions and support to manage the sector's sustainability. The inability to provide State patronage to NSMA and CMA in the form of conducive policy, enforceable regulatory frameworks and affordable finance, resulting in suboptimal sector performance, will have a negative impact on the ocean's health.

4. Conclusions

Small-scale aquaculture under NSMA and CMA plays a significant role in food security, livelihoods, nutrition and health. Some species and well-managed systems have few or no negative impacts on the ocean health (e.g. seaweeds and molluscs). However, the debate on whether the socioeconomic and environmental benefits of certain species and systems (coastal shrimp and nearshore fed-fish aquaculture) currently outweigh their potential negative impacts on the ocean's health continues.

The review of aquaculture in the second *World Ocean Assessment*, unlike in the present *Assessment*, addressed the full spectrum of aquaculture and its benefits and threats. It also pointed out several key knowledge gaps. It mentioned the public debate on the increasing dependence of developed countries on farmed seafood imports from developing countries and insecurity regarding product environmental, social and safety credentials, as well as scientific uncertainties and conflicting information on issues relating to seafood consumption. During the past few years, the application of third-party certification systems covering environmental, social and food safety concerns related to seafood has increased and improved, addressing seafoods originating from large-scale aquaculture. However, third-party certification requires further efforts to address the impacts and concerns of products originating from small-scale NSMA and CMA.

The present review noted the lack of specific laws governing small-scale NSMA and CMA that have been developed and enforced, especially in Latin America and Africa. Furthermore, programmes supporting aquaculture smallholder performance and sustainability are scarce worldwide. State-provided aquaculture extension services are usually insufficient, and NSMA and CMA actors do not have the resources to access such services on the open market. In addition, due to uncertainty and the lack of disaggregated data on small-, medium- and large-scale aquaculture, it is difficult to understand the contributions and impacts of each subsector. Better data would allow for more effective policies and practices. These shortfalls may lead to negative impacts for the ocean's health if not addressed in a timely fashion.

States should pay greater attention to NSMA and CMA under their blue economy development programmes, which will collectively contribute to global food and nutrition security and to improving livelihoods, while maintaining and improving the ocean's health. National laws and regulations need to be clear and promote growth in NSMA and CMA while prioritizing access to resources for vulnerable populations directly and indirectly involved in these sectors. New business innovation models allowing accelerated permitting of lower-trophic-level species such as seaweeds and mussels, along with other species cultures in the same locations, should be considered.

Considering the potential negative impacts of the aggregation of small-scale operations, spatial planning and addressing carrying capacity limitations, including integrated multi-trophic production systems, should be encouraged at the national and regional levels. Climate-driven technologies and practices, such as climate-smart and restorative aquaculture and economic models, should be promoted and implemented. It is

also important to address capacity development on governance and entrepreneurial skills related to NSMA and CMA at all levels.

Best management practices, including biosecurity measures, such as the progressive management pathway for aquatic biosecurity, need to be implemented. The use of genetically improved farmed types and non-native species can improve production efficiency and increase profits from aquaculture, but they can also have an adverse impact on the ocean and coastal areas. Risk analysis,[1] the precautionary approach[2] and the application of international codes of practice[3] are recommended to optimize the use of these farmed types and avoid negative impacts on the world's oceans and the aquaculturists that use them. Increased support for value-added product development and access to markets is needed.

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Subchapter 1E
Seafood processing[1]

Key points

- Seafood processing, marketing and trade are crucial dimensions of the global fishing sector, with an estimated value of about $195 billion in 2022, providing more than 3 billion people with animal protein as a primary source (FAO, 2024). Seafood broadly accounts for aquatic foods (fish, invertebrates and seaweeds), sometimes also referred to as blue foods, sourced from or cultured in oceans, lakes, rivers and seas.
- Due to the high perishability of fish and fishery products and their importance in nutrition security and global trade, effective and efficient processing techniques are imperative to extend shelf life, reduce post-harvest losses, improve revenues and enhance nutritional value (Ghaly and others, 2010; FAO, 2024). The present subchapter is focused predominantly on wild-capture fisheries and the post-harvest stages, i.e. processing, marketing, trade and consumption. It builds on the second *World Ocean Assessment* in prioritizing seafood and aquatic food systems within the United Nations Decade of Ocean Science for Sustainable Development, as well as the Sustainable Development Goals.
- By minimizing loss and waste through best management practices and ensuring the availability of high-quality seafood, the post-harvest sector directly contributes to Goals 2 (zero hunger) 3 (good health and well-being), 8 (decent work and economic growth), 10 (reduced inequalities) and 12 (responsible consumption and production). It gives the processing industry an opportunity to remain lucrative in global seafood markets as well as support Goal 14 (life below water).
- However, increased mechanization and globalization have also led to challenges such as loss of employment, reduced access to local fish products, food insecurity and the corporate takeover of smaller local businesses. In effect, post-harvest utilization and the value chain approach have supported management measures aligned with the Goals and other multilateral commitments such as the African Development Bank (AfDB) Feed Africa strategy (AfDB, 2016), FAO blue transformation initiatives and the United Nations Industrial Development Organization (UNIDO) blue industry and value chain approach.
- The present subchapter assesses the social drivers and impacts along the fish supply chain, suggests pathways for sustainable processing and defines governance mechanisms that promote policy harmonization and supply chain coordination. It concludes with key takeaways and future recommendations for the sustainability of the seafood processing sector. It is aligned with many international governing instruments, including the *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* (FAO, 2015).

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[1] The present subchapter is closely aligned with other subchapters in chapter 1 on food systems, as well as the relevant chapters on human dimensions in section 5, such as those on trade, small-scale fisheries, the coronavirus disease (COVID-19) pandemic, industrial fisheries, equity and well-being.

1. Introduction and background

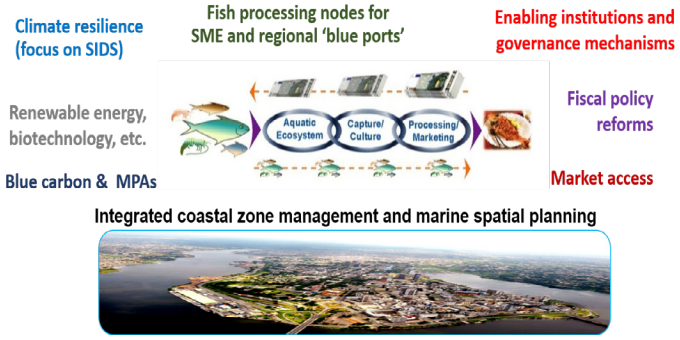
Fish production chain

Seafood processing is part of the fish production chain, which spans from oceans to plates. The fish production chain consists of three main interconnected stages: pre-harvest (aquatic ecosystems), harvest (capture or culture activities) and post-harvest (processing and marketing), as defined by Kooiman and others (2005). The latter stage is focused on processing, marketing, trade, including retail and wholesale, transportation, distribution and consumption. The subchapter emphasizes the importance of post-harvest and processing techniques, especially in small-scale fishing communities where community-based solutions are increasingly important to ensure food and nutrition security (Lowitt, 2013; FAO, 2024; Pérez-Escamilla, 2024). By implementing effective processing techniques such as chilling, freezing, canning, smoking, drying and other value-added methods, fish value chains can be transformed to support food and nutrition security, job creation and export earnings (FAO, 2024). Appropriate infrastructure, including landing sites, cold rooms or access to ice, improved or modern processing facilities, fish marketing outlets and efficient distribution channels can minimize post-harvest losses (FAO, 2020; Bavinck and others, 2005; Siddiqui and others, 2024).

Post-harvest losses are often caused by spoilage due to improper handling or inadequate infrastructure, reduce the overall yield and result in economic losses (Thorpe and others, 2005). In the case of sub-Saharan Africa, where essential infrastructure is limited, the majority of post-harvest losses occur at the production level (39%), followed by handling (36%), transportation and distribution (13%), processing (7%) and consumption (5%) (Abelti and Teka, 2024). This amounts to one third of total production and financial losses of between $2 billion and $5 billion (Abelti and Teka, 2024). Modern technology and appropriate infrastructure not only enhance food safety and security but also help to maximize economic benefits, contributing to the achievement of the Sustainable Development Goals. Attention to the composition of the labour force and corporate ownership models is therefore important. Moreover, ensuring equity and social inclusion in the seafood industry determines whether local fishing communities can fully reap the benefits of their resources and these advancements (FAO and others, 2023).

Although a fish production chain approach is applied by focusing on supply and raw material flows and an ecosystem approach (Thorpe and others, 2005), the value chain concept is complementary as a development paradigm to increase efficiency and reduce post-harvest loss (Gudmundsson and others, 2006). It is focused on improving quality and price and provides better opportunities for employment and nutritional security (Khan and others, 2021).

Figure I
Fish production chain



Source: Bavinck and others, 2005.

Processing and value addition

Processing, and the corresponding value addition, is the most important stage in the fish production chain. Various stakeholders transform harvested or cultured raw seafood into high-value products with a longer and more stable shelf life, catering to diverse consumer preferences and boosting economic value (Se-Kwon, 2014; Pinfold, 2007). Processing methods and product differentiation strategies vary across communities, regions and continents. These variations are influenced by factors such as local preferences, cultural traditions, availability of resources, technology, income levels, infrastructure, and labour and market dynamics. Socially, processing and the product differentiation stage offer numerous benefits, such as extended operational periods for processing plants and a reduction in repetitive strain injuries for workers, and allow for a greater diversity of fishery products, including repurposing of by-catch, benefiting both fishers and consumers. However, the growing reliance on migrant and forced labour on fishing vessels and processing plants, coupled with an increase in corporate mergers, raises human rights concerns as well as the fact that many of

the potential benefits might not be fully realized by local fishing communities.[2]

Fish as superfoods

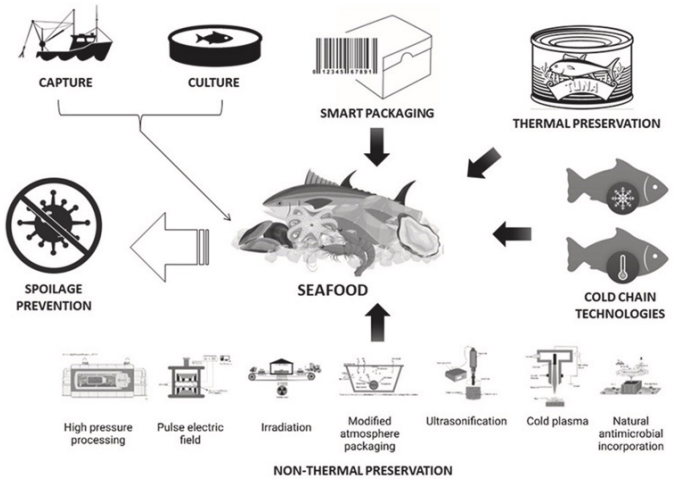
Seafood is a major source of animal-based protein, nourishing about 3.2 billion across the globe (FAO, 2024). It contributes directly to ending hunger (Goal 2) and responsible consumption and production (Goal 12) and enhances human well-being (Goal 3). The significance of processing and extending the shelf life of fish is very important, given that fishery products are highly perishable and susceptible to disease and infection. As seafood is processed into various product types, its high demand and consumer buying power make it the most traded food commodity globally (FAO, 2024; Bellmann and others, 2016). Fish is considered a superfood, essential for overall well-being and rich in essential and highly bioavailable nutrients, including omega-3 fatty acids, vitamins (A, D and B12) and minerals, making them a critical component of a healthy diet (UN Nutrition, 2021; Issifu and others, 2022). Access to adequate infrastructure and proper processing techniques, such as freezing and canning, not only extend the shelf life of fish but also help to preserve nutritional value, ensuring that health benefits remain accessible to a broader population even during pandemics (Khan and others, 2021).

Circular economy and seafood processing

Applying circular economy principles to seafood processing brings additional benefits by maximizing resource efficiency and including multispecies management plans, energy use and decarbonization (Cooney and others, 2023). Modern, improved traditional processing techniques increasingly seek to integrate economic efficiency, reduced fuel use and environmental conservation, demonstrating the multifaceted benefits of these practices (Harrison and others, 2020a; Siddiqui and others, 2024). Recently, much of the discarded food waste has been developed into affordable and nutritious products owing to their nutritional value (Peñarubia and others, 2023), incorporating added nutrients such as iron, calcium and other micronutrients that can address deficiencies in human health (UN Nutrition, 2022). While advanced processing may enhance economic value through reduced losses as well as product differentiation, it may also support sustainability goals by reducing fishing pressure with higher revenues and focusing on socioeconomic benefits (see figure II).

Fish processing is often mandated under State laws and through fisheries management policies, bureaux of standards or competent agencies tasked with labelling, packaging, branding and exporting to ensure alignment and global standards (Kumar and others, 2020; UNIDO, 2024). To gain a competitive advantage across the value chain, seafood processors and stakeholders adopt strategies to differentiate and label their products according to sustainability criteria. Eco-labels such as the Marine Stewardship Council[3] and ECOMARK and traceability tools including ThisFish[4] and Vericatch[5] play a key role in appealing to consumer awareness. These tools and labels often help to uphold chain of custody rules, enhance product competitiveness, extend shelf life, promote food security and support conservation. However, they have proven complex and at times controversial, compromising integrity and intended principles (Blasiak and others, 2021; Nakamura, 2024).

Figure II
Seafood processing infrastructure and techniques



Source: Siddiqui and others, 2024.

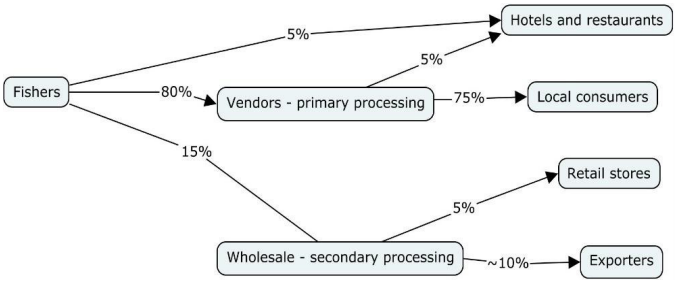
Processing methods and product differentiation

Processing and product differentiation are important for two reasons: (a) to increase the profit margin by catering primarily to various markets in middle- and high-income countries; and (b) to extend shelf life, especially in low-income countries lacking improved cold

2 See www.humanrights.dk/promoting-human-rights-fisheries-aquaculture.
3 See www.msc.org.
4 See https://this.fish.
5 See https://vericatch.com.

chain infrastructure and purchasing power, but with high demand for nutritious and affordable seafood. Three processing methods are therefore used globally: primary processing (in fresh or cured form without change in texture or taste), secondary processing (with some changes to taste and form) and tertiary processing (with changes in form and taste and an increase in shelf life). Fish value chains can be quite short, with fresh products distributed directly to local markets and consumers, or can be processed and traded through local vendors, wholesalers and international buyers with export licences (see figure III).

Figure III
Product flows and market share as evident in the Caribbean



Source: Khan and others, 2019.

The seafood processing industry employs diverse techniques to extend shelf life and cater to local and regional preferences. For instance, freezing is known to preserve nutritional quality and is widely used in regions with advanced cold chains, such as Europe and North America, while canning ensures long-term preservation and is common in Asia and South America. Traditional smoking, prevalent in northern Europe, sub-Saharan Africa and parts of North America, imparts flavour and enhances preservation (FAO, 2022) but is associated with deforestation concerns. Smoking also risks contaminating fish with carcinogenic polycyclic aromatic hydrocarbons and other toxins (Bwala, 2023). While Scandinavia excels in smoked salmon and pickled herring, the Mediterranean offers traditional salted and dried fish (e.g. *bacalao*) in Italy and Portugal, which is a staple ingredient in many traditional dishes such as *brandade de morue*, a creamy fish spread made with salt cod, as well as cured and canned fish. Traditional drying and salting methods are common in South-East Asia and sub-Saharan Africa due to their accessibility and cultural taste, as well as their nutritional value (Johnson and others, 2023). This practice is also linked to the lack of cold room infrastructure and ice to preserve fresh fish (Bavinck and others, 2023).

Regional diversity and length of value chains

In regions where tertiary processing is common, seafood can be made into snacks and condiments. For instance, South-East Asia is known for producing shrimp paste and dried fish, while Japan is renowned for sashimi-grade fish. In the Caribbean region, as shown in figure III, where fresh fish is invaluable to the tourism and hospitality industry, such as in hotels, the fish value chain can be short for some commercial species such as live lobsters and longer for species such as groundfish, depending on processing requirements, consumer markets and price premiums. In western Africa, small-scale tuna canning and large-scale trans-shipment contribute to national economies in coastal ports such as Tema and Abidjan (see box 1), as these processing enterprises provide processed fish for export, especially to regional landlocked countries, as well as for local nutritional needs (Ayilu and Nyiawung, 2022).

Box 1
Tuna processing and trans-shipment in West Africa

Abidjan is the leading commercial fishing port for tuna trans-shipment and the small-scale canning industry in West Africa. The fishing port, part of the wider Autonomous Port of Abidjan economic zone, is a State-owned enterprise with capital of about $170 million in 2022. It handles close to 1 million tons of seafood per year, 35% of which is tuna. Tuna fishing is dominated by three main species: yellowfin (*Thunnus albacares)*, skipjack (*Katsuwonus pelamis)* and bigeye (*Thunnus obesus)*. These tuna stocks are mainly caught by vessels flying Spanish and French flags and the national Ivorian fleet and trans-shipped to local canneries. In 2023, around 70 vessels trans-shipped to three local canneries operating in Côte d'Ivoire, which produce about 60,000 tons of canned seafood per year, creating more than 3,000 jobs, the majority of which held by women. About 15 local companies also operate at the port to facilitate a cold room seafood network with up to 70,000 tons of storage capacity to address seasonality and price fluctuations. The tuna industry also supports local consumption of the popular Ivorian dish *garba*, which contains cured and deep-fried tuna fillets.

2. Pressures and impacts

Demand-driven fish chains

Various pressures and drivers influence the production and productivity of aquatic foods and fish value chains. It has been argued that in regions where there is high demand for fish, in combination with sequential exploitation and mismanagement, raw material supply can be a challenge for processing as plants close and processing jobs are lost (Berkes and others, 2006). The earlier collapse of some stocks of orange roughy (*Hoplostethus atlanticus*) in Australia and New Zealand, cod stocks on the Grand Banks (*Gadus morhua*) and some groundfish stocks in New England all indicate human-induced drivers of change, with processing jobs at risk (Ludwig and others, 1993; Khan and Neis, 2010). Effective governance strategies are essential to address these multifaceted challenges to ensure sustainable fisheries while safeguarding ecosystems in the face of environmental changes (Jentoft and Chuenpagdee, 2009; d'Armegnol and others, 2018). Collaborative approaches that involve local communities, policymakers and scientists can foster resilience and promote long-term sustainability in fisheries resources (Ommer and Neis, 2014).

Technological innovation

Technological innovation has had a profound impact on fishing efficiency, also influencing the supply of raw materials, fish processing measures and product development. Recent research underscores the necessity for the implementation of policies that encourage responsible innovation, thereby ensuring that technological advancements contribute to the sustainability of fisheries and the development of premium seafood products (Siddiqui and others, 2024). While economic incentives such as subsidies can facilitate technological advancement and enhance fishing capacity (with offshore processing infrastructure and higher revenues), they can also result in overcapacity and unsustainable practices if not properly regulated (Sumaila and others, 2021; Cisneros-Montemayor and others, 2020). For example, subsidies that promote fuel consumption may provide an incentive for increasing fishing efforts, which can undermine the health of fish stocks, especially in deep-sea environments (Foley and others, 2011; Sumaila and others, 2010). Recent estimates of global fishery subsidies suggest that subsidies provided in the preceding decades may have halted, but the bulk of harmful "capacity-enhancing" subsidies, particularly those for fossil fuels, have increased as a proportion of total subsidies (Sumaila and others, 2019). Although discussed in the second *World Ocean Assessment*, the matter remains pertinent to the present *Assessment* given the evolving policy climate such as the World Trade Organization (WTO) Agreement on Fisheries Subsidies of 2022 and recent additional provisions during the WTO thirteenth Ministerial Conference in Abu Dhabi in March 2024. Additional provisions on overcapacity and overfishing subsidies are still being proposed and debated without consensus (Irschlinger, 2024). Moreover, subsidy research is still topical and relevant, indicating the need for better policy and practice for resource sustainability and value chain benefits (Soeparna and Taofiqurohman, 2024; Revollo-Fernández and others, 2025).

Given the observed increase in fishers' incomes, a notable surge in demand for fish and seafood is expected, with considerable pressure being exerted on supply chains and ecosystems already operating under considerable strain (Bennett and others, 2022). As populations expand and urbanization accelerates, the demand for accessible and affordable seafood options intensifies, resulting in a complex interplay between supply constraints and consumer expectations (FAO and others, 2023). This growing demand presents a dilemma for fisheries management, as stakeholders must reconcile the imperative for economic returns with the need for sustainable fishing practices (see box 2). According to FAO (2024), maintaining the current consumption levels of aquatic animal foods until 2050 will require a huge reduction in catch and improved post-harvest utilization.

Sustainable fishing practices, bolstered by cutting-edge technologies such as mobile applications and digital platforms, are providing fishers with real-time market data, thereby enhancing supply chain efficiency and traceability benefits (Bennett and others, 2022). It is of paramount importance for policymakers to establish a regulatory framework that fosters sustainable post-harvest practices and technological advancements in a manner that safeguards the environment and benefits fishing communities through chain of custody, certification and price premiums.

Box 2
Response by Norway to pressures with integrated fisheries management systems

Norway has implemented an integrated fisheries management system that combines scientific research, regulatory measures and stakeholder engagement to ensure sustainable fisheries. The system includes strict quotas, real-time monitoring of fishing activities and comprehensive data collection. By basing management decisions on robust scientific research and involving stakeholders such as fishers, scientists and regulators, the Norwegian model enhances the effectiveness and sustainability of fisheries governance. An emphasis on science-based management, real-time monitoring and collaborative governance is crucial to maintaining sustainable fisheries (Paolo and others, 2022).

Impact of non-human-induced changes

Seafood products and processing methods are highly influenced by both natural and human-induced drivers of change at multiple scales. In recent years, the dynamics of commercial fish value chains have increasingly revealed a fundamental tension between demand-driven and supply-driven factors (Gudmundsson and others, 2006). The prevalence of supply-driven fish value chains frequently gives rise to considerable obstacles, including overcapacity, which can result in unsustainable fishing practices, coupled with ecological shifts (Khan, 2012). Poor and inconsistent harvest rules across different regions complicate resource management outcomes and often lead to overfishing, further destabilizing ecosystems (Berkes and others, 2003; Hilborn and others, 2020).

The sustainability of raw material supply in the harvest stage of the fish chain is highly important, as it influences the volume and value of the catch, therefore affecting the corresponding processing methods, product types and market viability. Other driving factors such as natural variability and El Niño Southern Oscillation events can affect fisheries ecosystems, raw material supply and seafood processing opportunities (Kumar and others, 2014). Recent studies indicate that climate change alters marine ecosystems, affecting the distribution and abundance of key commercial species, which, in turn, influences raw material supply chains (Cheung and others, 2021). For instance, rising sea temperatures and ocean acidification can lead to shifts in fish populations, affecting fish availability and the livelihoods of communities reliant on these resources (Intergovernmental Panel on Climate Change, 2022). In maritime regions where fisheries livelihoods are highly at stake, such as in eastern Canada, both place-based interventions (at the municipal and district governance levels) and sector-based interventions (at the provincial and federal management levels) are needed for sedentary species such as lobsters (Khan and others, 2016). In many parts of the developing world, climate finance has been sought through multilateral banks to support nature-based solutions and other forms of institutional capacity in order to be resilient.[6]

To address these challenges, a multifaceted governance approach is required, encompassing improvements in resource management, investment in environmentally sustainable practices and the promotion of responsible production and consumption. Moreover, to develop effective strategies that support economic viability, it is essential to comprehend the interplay between drivers of production capacity, labour and corporate ownership practices, environmental impacts and integrated responses to stressors (Khan and Cundill, 2019).

3. Socioeconomic considerations

Ethical issues during seafood processing

Social and ethical considerations in seafood processing are important as they support human rights values (for details, see subsect. 5B, chap. 5). Ensuring safe working conditions and fair wages and prohibiting forced and child labour are essential for protecting workers' rights within the fish processing sector. Yet migrant and forced labour exist in fisheries around the world, especially in relation to seafood processing (International Labour Organization (ILO), 2016). The ILO Work in Fishing Convention (No. 188) establishes international standards for labour conditions, highlighting the importance of its adoption and enforcement to promote ethical labour

6 See www.thegef.org/what-we-do/topics/country-engagement-strategy.

practices. However, the list of countries that have not ratified the Convention remains extensive,[7] and much work remains to be done to secure the basic human rights of fishers and workers across the global seafood supply chain (Guelker, 2023).

The ILO Convention is crucial to ensure that all workers in the fishing sector enjoy decent working conditions, in accordance with Sustainable Development Goal 8, thereby fostering a more responsible seafood sector.

Safe, well-paying employment opportunities are a crucial form of equity for seafood processing licensing agreements, especially for international companies relocating to areas with weaker labour rights and regulations (Knott and Marschke, 2020). Ethical and social best practices should ensure that the economic benefits of the seafood sector contribute positively to coastal communities, including fair compensation for local fishers and support for community development initiatives (Marschke and others, 2018). Integrating these social considerations benefits workers and living aquatic resources and enhances the overall integrity of socioecological systems (see box 3).

Box 3
Responsible fisheries management certification in Alaska

The responsible fisheries management certification in Alaska is a voluntary third-party programme that verifies the sustainability of fisheries based on internationally recognized standards. The certification emphasizes local management and stakeholder involvement while aligning with global sustainability benchmarks. A key feature of the certification is its transparency with publicly available assessment reports and stakeholder consultations. The model illustrates the significance of local involvement, alignment with global standards and transparency in certification processes for effective fisheries governance (Packer and others, 2019; Lue and others, 2022).

As consumer demand for ethically sourced seafood increases, the seafood processing sector must prioritize labour, animal rights, transparency and traceability in its supply chains to meet these expectations (Österblom and others, 2015).

Gender equity and social inclusion

Promoting gender equity and social inclusion in seafood processing is essential to ensure that everyone benefits from the fisheries sector (Ommer and Neis, 2014). As discussed fully in subsection 5B, chapter 5, increasing attention has been paid to the crucial roles that women play across fisheries value chains, particularly in processing, marketing, distribution and retail (Harper and others, 2013; Kleiber and others, 2017; Pedroza-Gutiérrez and Hapke, 2022; Wabnitz and others, 2021). The *Illuminating Hidden Harvests* study (FAO, Duke University and WorldFish, 2023) estimated that 45 million women worldwide participate in small-scale fisheries value chains or engage in subsistence activities, which translates to 40% of all people active in the subsector. Women represent 15% of those engaged in the pre-harvest segment of the small-scale fisheries value chain (e.g. gear fabrication and repair, bait and ice provisioning, boat building), 18.7% in the harvesting segment (including vessel-based and non-vessel-based activities) and 50% in the post-harvest segment (e.g. processing, transporting, trading, selling), and account for 45% of all actors engaged in small-scale fisheries subsistence activities (FAO and others, 2023). Their specialized knowledge of marine resources, especially in shallow waters, is vital not only for local economies and food security, but also for cultural continuity, food sovereignty and adaptation to environmental change (FAO, 2022; Harper and others, 2020; Tilley and others, 2021; McLeod and others, 2018).

Nevertheless, women often face persistent structural barriers. These include gendered expectations around roles and responsibilities within households and communities, which can influence access to resources and markets, time and decision-making opportunities. Women's contributions across fisheries value chains are also frequently undervalued due to a focus on commercial industrial fisheries, which are typically male-dominated (Barclay and others, 2021). Constraints in accessing business development services and limited opportunities for training in areas such as financial literacy, digital tools and leadership further inhibit women's full engagement in value chains.

Achieving more equitable outcomes requires a better understanding of how gender intersects with other dimensions (Crenshaw, 1991) of identity, including age, class, race, disability and citizenship status (Knott, 2016;

[7] See https://normlex.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:11310:0::NO:11310:P11310_INSTRUMENT_ID:312333:NO.

Knott and Marschke, 2020; Sangaramoorthy, 2019). These factors shape access to resources and opportunities and participation in decision-making, as well as vulnerability to exclusion and exploitation (Adam and others, 2024; Galappaththi and others, 2021; Frangoudes and others, 2019).

Efforts to promote gender equality must move beyond stand-alone initiatives to engage with the wider social and organizational contexts that influence participation, recognition and outcomes across the sector. While scholars and practitioners have argued that gender equality can be achieved through the implementation of gender-sensitive policies and targeted programmes, this needs to be broadened to reflect local social and institutional contexts, including partnerships and governance arrangements (Mangubhai and others, 2022; Wabnitz and others, 2025). More integrated systemic approaches, drawing on intersectional frameworks and acknowledging that social inequalities exist both between and among groups, including but not limited to gender, can lead to more inclusive recognition of contributions across the sector (Wabnitz and others, 2021). Such an approach not only is aligned with sustainability goals, but also strengthens the resilience and productivity of fisheries systems and value chain actors (Barclay and others, 2021).

Stakeholder interactions: winners and losers

Stakeholders are broadly defined along the fish production chain as those that govern (e.g. fisheries managers, maritime observers, custom officers, non-governmental organizations (NGOs)) and those that are governed, including fishers, processors, traders and cooperatives (Bavinck and others, 2005; Khan, 2012). Fisheries management and governance practices are influenced by these social relations that involve power and authority, especially legislative and regulatory norms. When properly diagnosed and understood, power analyses could support cooperation among stakeholders, improve compliance with rules, foster equitable distribution of benefits and mitigate conflicts (Khan and Neis, 2010). In this context, power and political economy are essential social issues in governance and governing interactions. Often, stakeholder interactions and social relations are hidden or invisible, or are intangible or translucent, until conflicts or dissension arise or agreements are signed and announced.

Groups, including labour unions, fisher cooperatives, processor associations and trade hubs, and their productive bargaining power, are all mechanisms to leverage resources and advocate for fair gains and access to resources. Given the importance of stakeholders along the fish chain and the sustainability of the resource, the procedural and equitable distribution of benefits is important. This will take shape differently whether in small-scale fisheries, industrial commercial fisheries or distant-water fisheries. Small-scale fisheries, which provide essential nutrition and income to millions globally, often encounter obstacles such as restricted access to markets, insufficient post-harvest infrastructure and food waste (Chuenpagdee and Rocklin, 2016). Conversely, distant-water fisheries play a significant role in the global seafood supply, but can contribute to overfishing and ecological degradation in the absence of offshore monitoring and control mechanisms, raising concerns about resource sustainability and equitable distribution to local communities (Daw and others, 2021; Torreblanca and others, 2022).

Moreover, collaboration among stakeholders, including government agencies, NGOs and the private sector, is crucial to develop comprehensive policies that address multifaceted issues (Jentoft and Chuenpagdee, 2009). Such inclusive policies can foster a sustainable and equitable fisheries sector, ensuring that the needs of stakeholders are met adequately.

4. Sector-relevant governance

Governing fish processing activities

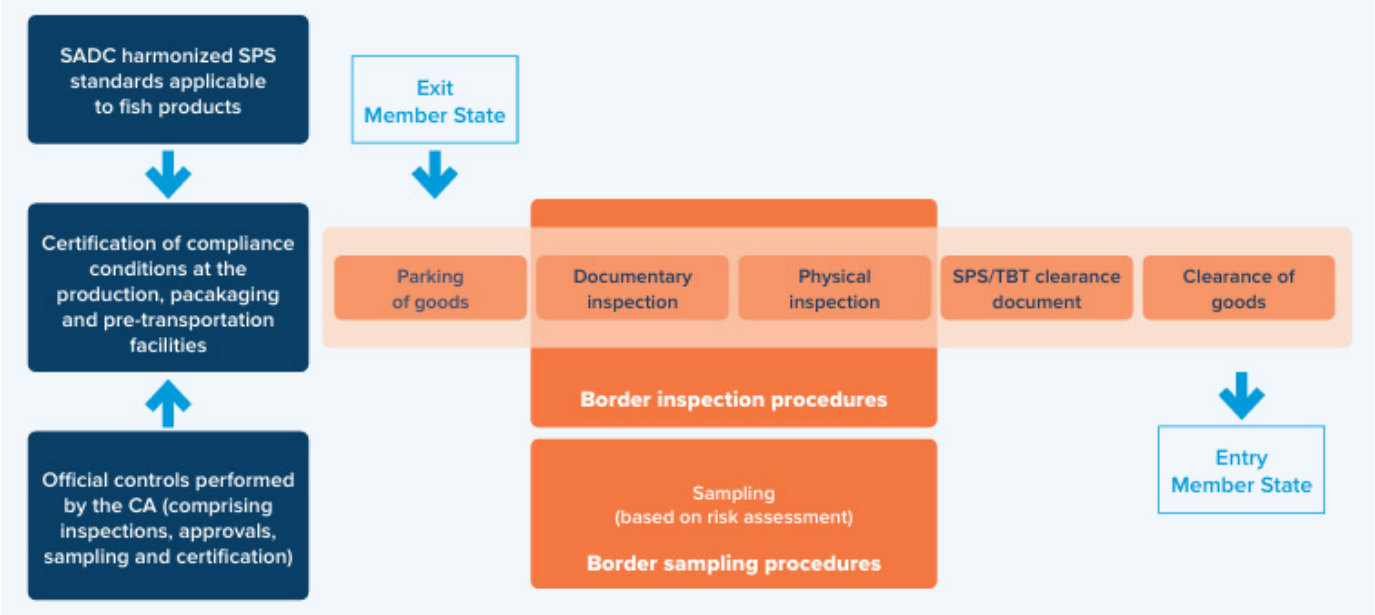
The seafood processing sector, which is integral to global food security and economic growth, necessitates robust governance to ensure product safety, quality and adherence to international standards. Policy harmonization, which aligns regulations across jurisdictions, is a critical factor in this process. It facilitates product design and standards and ensures quality control and safety. Adherence to the international best practices and policies set by WTO, FAO and ILO is crucial for global market access, strengthening competitiveness, upholding ethical standards and fostering sustainable growth. This alignment increases processing efficiency, reduces trade barriers, enhances market access and increases consumer confidence.

Harmonized policies eliminate regulatory discrepancies that function as non-tariff barriers and facilitate international trade (Jouffray and others, 2019). The alignment

of standards across countries ensures that seafood products meet uniform safety and quality requirements, thereby improving market access. Electronic sanitary certificates have further streamlined trade processes, enhancing transparency and risk management (Lee, 2024). For instance, harmonizing sanitary and phytosanitary measures established by WTO is crucial for protecting health and maintaining the integrity of the seafood supply chain (Sumaila and others, 2020; Tickler and others, 2018).

As seafood is one of the most traded agri-commodities (Smith and others, 2010), its processing is closely linked with regional markets and export revenues in most coastal countries (see subsect. 5A, subchap. 1F). For instance, experience gathered in the Southern Africa Development Community (SADC) showed that integrating fishery commodities into the One Stop Border Post initiative is the most practical trade facilitation approach in terms of standardization and policy harmonization. This approach is often seen as a type of "market export", whereby high-value commodities are processed for foreign exchange and regional benefits (Crona and others, 2016). The One Stop Border Post initiative involves placing officials of two countries in each other's border offices so that outward and inward clearance is carried out in one place sequentially (New Partnership for Africa's Development (NEPAD), 2022), thus providing an opportunity for joint, harmonized controls on each side of the border. The concept of a sanitary compliance and conformity assessment implementation framework through this initiative should address checks at borders as well as the application of the process control model for fisheries product quality and safety within the various fish value chains (see figure IV).

Figure IV
The One Stop Border Post approach for common processing standards and trade facilitation



Source: UNIDO, 2024.

Instruments of governance

Effective governance of seafood processing requires a comprehensive approach that integrates a variety of regulatory instruments at the local, regional and international levels, from harvesting and processing to marketing. These governing frameworks are crucial for addressing the multifaceted challenges of the seafood industry and for promoting practices that enhance economic sustainability and environmental stewardship (Khan and Chuenpagdee, 2014). The industry operates within a complex network of regulations to ensure food safety, protect labour rights and preserve the marine environment. These instruments include legal frameworks, international agreements, voluntary measures and organizational mandates that collectively oversee the management of value chains and the conservation of aquatic resources. Key instruments include:

- The United Nations Convention on the Law of the Sea and the FAO Code of Conduct for Responsible

Fisheries, which establish global standards for marine resource governance.

- The Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, which emphasizes international cooperation to ensure sustainable fisheries.
- The ILO Work in Fishing Convention, which sets forth international labour standards to ensure safe working conditions, fair wages and the prohibition of forced and child labour within the seafood industry.
- The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction, which recognizes the importance of conserving marine ecosystems for the sustainability of fisheries and aquatic food systems.
- The Kunming-Montreal Global Biodiversity Framework, established at the fifteenth Conference of the Parties to the Convention on Biological Diversity, which emphasizes the need for integrated approaches to biodiversity conservation and sustainable resource use.
- The WTO Fisheries Subsidies Agreement, which represents another critical element in global fisheries governance and is useful to curb harmful subsidies that contribute to overfishing and illegal, unreported and unregulated (IUU) fishing, thereby promoting cooperation, fairness and sustainable fishing practices.
- The Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing, which is legally binding and empowers port States to deny foreign vessels suspected of having engaged in IUU fishing from using their ports to land catches.
- The *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication*, which is a negotiated international instrument endorsed by the FAO Committee on Fisheries and include a dedicated chapter on value chain, post-harvesting and trade.
- The Fisheries Transparency Initiative, which strengthens governance by promoting transparency and accountability within the seafood processing industry.

In addition to international and regional frameworks, regional fisheries management organizations (RFMOs) and regional fisheries bodies play a pivotal role in the governance of shared fish stocks that spans across national boundaries. National regulations further complement international and regional frameworks by addressing specific local needs and conditions. For instance, the Food Safety Modernization Act of the United States of America and the General Food Law Regulation of the European Union impose stringent food safety and traceability requirements on seafood processing facilities.



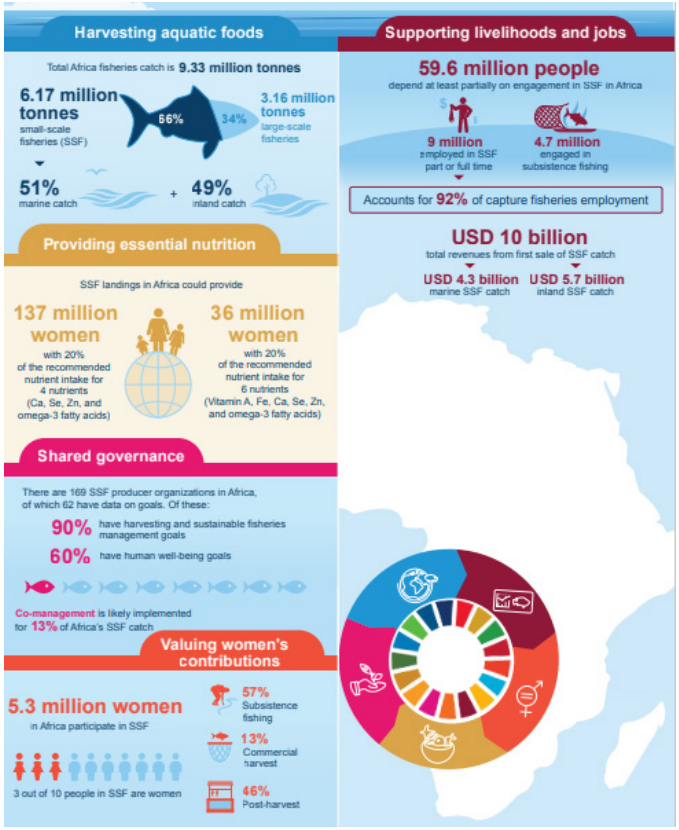
Andrey Nosik

5. Sustainability pathways

Management controls

Fisheries management controls influence access rights, raw material supply and the profitability of fish commodity chains. Often, sustainability parameters such as catch per unit effort are used to address stock abundance and the viability of fish value chains. This is a useful policy instrument that controls fishing efforts, and the question is how best to optimize or "satisfice" fisheries management goals (Miller and Shelton, 2010). A combination of input and output control measures may be appropriate in some instances, whether total allowable catch, vessel or individual quotas, seasonal closures, community quotas, gear restrictions, permits and licences. The choice of measures could be a function of objectives, cost and national priorities. These management controls help to maintain fish production chains, especially in the small-scale sector, and to ensure full benefits for society (see figure V).

Figure V
Small-scale fisheries' contribution to processing and value addition benefits in Africa



Source: FAO and others, 2023.

In addition to management control measures that are designed to support an ecosystem approach, there are market-based incentives for the sustainability of the seafood industry aimed at ensuring fair trade and stewardship and addressing concerns relating to overfishing (see box 4). These market-based tools have ensured that each player in the seafood industry is held accountable for the course of sustainability practices in the complex international seafood trade, especially regarding mislabelling (Jacquet and Pauly, 2008). The adoption of eco-certification processes, for instance, strives to improve awareness and information-sharing, which may be empowering for the seafood industry.

Box 4
Comprehensive fisheries management system of Iceland (Organisation for Economic Co-operation and Development (OECD), 2017)

Iceland developed a comprehensive fisheries management system that integrates sustainability, traceability and quality assurance. Central to it is a quota management system that allocates fishing rights to individual vessels, ensures sustainable harvest levels and prevents overfishing. Advanced traceability systems track seafood products from catch to consumers, ensuring compliance with regulatory standards and enhancing consumer confidence. The active involvement of stakeholders, including fishers, processors and regulators, fosters a collaborative approach to fisheries management, highlighting the significance of quota management, transparency and stakeholder engagement for effective governance.

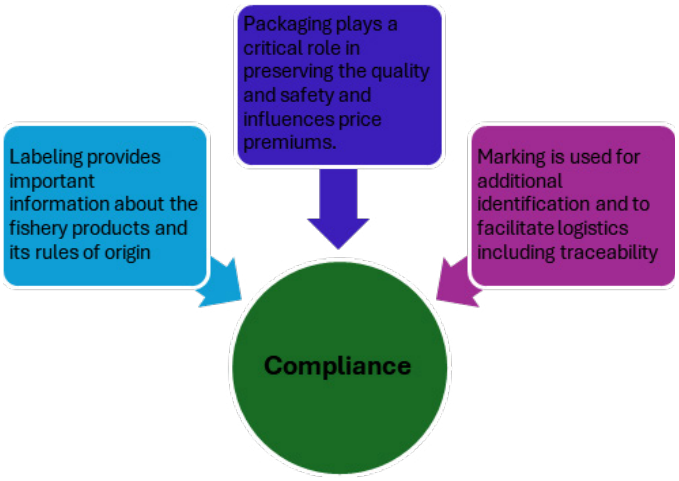
Quality infrastructure and standardization

Quality and safety are crucial drivers of sustainable seafood trade and processing methods. Consumers must be convinced that seafood is safe from foodborne pathogens, mycotoxins and other production hazards. Similarly, seafood buyers must meet increasingly robust food safety and quality control standards. The difficulty of establishing cause and effect along value chains creates an urgency to invest in mycotoxin prevention and other hazards (Akintola and others, 2022). In tropical settings, where microbial activities are predominant due to high

temperatures and humidity, post-harvest activities might be compromised by growth of fungi moulds and bacterial infection. Understanding post-harvest best practices is imperative for social and economic reasons in the context of safety and seafood quality.

A prime example is the implementation of hazard analysis and critical control point systems, which are globally recognized approaches for improving food safety in seafood processing (Okeke-Ogbuafor and Gray, 2021). These systems are designed to proactively identify and control potential hazards and prevent food safety issues before they occur. Adopting these systems is often a prerequisite for accessing major international markets such as the European Union and the United States, where strict quality and safety standards are enforced (Kurnia and others, 2020; Naabi and Bose, 2020). Consequently, operators implementing such systems and prerequisite programmes are better positioned to compete globally, thus enhancing their market access, competitiveness and consumer confidence. Policies must therefore be designed to maximize economic benefits while simultaneously enabling the prosperity of local markets and communities. As shown in figure VI, processing activities within the fish production chain are influenced by a continuum of management measures in the pre-harvest and harvest/culture stages and have an impact on post-harvest measures as well as retail trade and consumption patterns. These consumption patterns and dietary preferences within agrifood systems and commodity chains have implications for human well-being (see figure VI).

Figure VI
Processing activities and implications for marketing and conservation practice



Source: UNIDO, 2025.

Building economic resilience under global change

As will be discussed in subsection 5B, chapter 7, global shocks such as the coronavirus disease (COVID-19) pandemic have affected fish harvesting and seafood processing, especially with social distancing, lockdowns and border closures to contain infection (Bennett and others, 2020). To be resilient under global change, multiple strategies must be deployed to address the public health, trade flows and nutritional needs of communities. In the absence of active fishing and processing, short-term health protocols and social safety nets are imperative (Khan and others, 2021).

Policy innovation and sustainability entry points

Five key takeaways are provided below as tenets for seafood processing to complement and align with other chapters of the third *World Ocean Assessment* on food systems, trade, small-scale fisheries, gender, industrial fisheries and well-being:

- **Sustainable Development Goals.** The seafood industry has made significant progress in aligning with global objectives such as Goals 2 and 14, contributing to sustainable marine governance and food and nutritional security. Processing methods such as freezing and canning have an adverse effect on the nutritional value of seafood while reducing post-harvest losses, thus supporting food security, livelihoods and economic prosperity. Processing methods also address gender, well-being, decent work, responsible consumption and production and climate action (Goals 5, 8, 10, 12 and 13).
- **Efficiency and value addition.** The fish production chain consists of interconnected stages in which effective post-harvest techniques reduce spoilage and add value. Processing methods such as chilling, freezing and curing are crucial in transforming raw seafood into more stable and marketable products, thus contributing to food and nutrition security.
- **Technological advancements.** Advances in technology and modern infrastructure, including automation, digital platforms and precision tools, have improved fish supply chain efficiency (Siddiqui and others, 2024). This is achieved by inactivating spoilage microorganisms and enzymes that contribute to the deterioration of the product over time (Russo and others, 2023). Technologies such as high-pressure processing, cold plasma and pulsed electric field processing are particularly effective in this regard (Russo and others, 2023). However, they also present

challenges that require regulatory frameworks in order to ensure long-term viability and sustainability.

- **Environmental and social pressures**. Factors such as adverse incentives and subsidies relating to overfishing, climate change and pollution pose risks to marine ecosystems, raw material supply and seafood production. Moreover, social issues such as labour rights, gender equity and social inclusion further challenge the industry's governance and demand policy reforms.
- **Governance and regulatory frameworks.** Effective governance of the seafood industry is essential for maintaining sustainability. International frameworks such as the United Nations Convention on the Law of the Sea and the WTO Fisheries Subsidies Agreement emphasize cooperation and regulatory harmonization to curb overfishing and ensure compliance with environmental and labour standards.

6. Summary and conclusion

In 2022, of the 165 million tons of fish destined for human consumption, live, fresh or chilled fish accounted for about 43% (FAO, 2024). This was followed by frozen (35%), prepared and preserved (12%) and cured (10%). Moreover, freezing is the main method of preserving aquatic foods, accounting for 62% of the 93 million tons of processed aquatic animal production for human consumption. This represents about 89% for direct human consumption, with the remaining 11% for non-food purposes such as fish meal in aquaculture and biofuel. Recently, much of the discarded food waste has been developed into affordable and nutritious products because of their nutritional value (Peñarubia and others, 2023), along with nutrients such as iron, calcium and other micronutrients that can address deficiencies in human health (UN Nutrition, 2021).

By addressing social and economic issues in coastal communities, the seafood processing industry can play a central role in promoting gender inclusion, fair wages and decent work conditions for all (Sustainable Development Goals 5, 8, 10 and 12). To achieve a more sustainable and equitable future for seafood processing, stakeholders are encouraged to adopt some key policy recommendations:

1. **Invest in public goods and fisheries governance.** Seafoods systems are governed by public institutions because of the common benefits to global citizens. Governments and industry leaders should therefore invest in natural capital assets and fisheries conservation, as well as appropriate technologies and modern infrastructure to ensure compliance with management best practices. These investments will drive compliance, reduce perverse incentives to overfish and cater to evolving consumer preferences and community benefits.
2. **Promote ethical labour practices and social equity.** Advanced processing techniques, especially for traceability and rules of origin, will play a pivotal role in compliance and meeting the diverse needs of stakeholders. However, technological innovation should not come at the expense of social inclusion and community resilience. In prioritizing and promoting social inclusion, it is important to ensure safe working conditions, fair wages, jobs for young people and gender equity at all stages of the seafood processing chain. Thus, Governments and industry actors could ensure that the ratification and enforcement of global labour standards to protect workers' rights and foster ethical consumption and production practices are sustained (ILO, 2016).
3. **Strengthen governance and policy harmonization.** As global demand for seafood increases, integrated policy frameworks and value chain enhancements must be aligned to foster a more inclusive and resilient sector. Policymakers must prioritize harmonizing regulations across jurisdictions to facilitate fair trade, uphold environmental standards and ensure that labour rights are met (Harrison and others, 2020b). Collaborative efforts between regional and global bodies will be essential to curbing overfishing, improving traceability and promoting sustainable fishing practices and processing methods.
4. **Upgrade infrastructure and build capacity.** Embracing circular economy best practices, such as renewable energy in processing plants and biodegradable packaging, will ensure that the industry remains aligned with sustainability principles and environmental stewardship. Developing nations and coastal communities require investments in cold storage facilities, modern processing plants and transportation networks to reduce post-harvest loss. Capacity-building programmes targeted at women,

young people and small-scale fishers will empower local communities, increase revenues and create more equitable opportunities within seafood value chains and the processing industry.

5. **Foster consumer awareness and demand for sustainable food products.** Consumer awareness and education campaigns in eco-labelling and sustainability certifications should be a priority for all economic sectors (businesses) and Governments to boost demand and enable more informed and sustainable purchasing decisions for seafood (Österblom and others, 2015).

By taking these sustainable pathways, the seafood processing industry can meet global challenges in the future, safeguarding marine ecosystems and ensuring the well-being of millions of people who rely on seafood as a vital source of nutrition, jobs and export earnings.

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Subchapter 1F
Trade

Key points

- The uneven distribution of aquatic resources has driven trade from the local to global levels for millenniums, but the share of marine production being exported has increased in recent decades. Specific trade patterns are mediated by differences in production and transport infrastructure, governance, economic factors and geopolitical relationships.
- Seafood trade can have positive or negative impacts on local environments, economies and communities, depending on the institutional and governance context.
- Trade regulations, certifications and traceability tools are emerging to support sustainable seafood trade, but their impacts and effectiveness require further analysis.

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1. Introduction

Aquatic resources are unevenly distributed around the world and human population centres are often distant from areas of high abundance. As a result, fish and other aquatic organisms (i.e. aquatic foods) have been traded for millenniums, with some communities specializing in production and trade in order to obtain other goods that are often not available locally. Aquatic food continues to be caught and farmed for subsistence, gifting, bartering and trade within communities, subnationally and internationally. In the present subchapter, trade is considered to include all exchanges of aquatic food for monetary or non-monetary benefit, but focused most prominently on international trade. In addition, the focus is primarily on trade in marine fisheries and aquaculture products (referred to as "seafood"), but it is often not possible to fully separate marine products from inland products in reported trade statistics. Therefore, the collective group of all farmed and wild-caught foods from marine and inland habitats is sometimes referred to as "aquatic foods". At the international level, aquatic food is among the most highly traded foods, with around one third of all production traded and a higher export orientation for marine wild-caught and farmed products compared with inland products (Asche and others, 2015; Gephart and others, 2024).

While economic theory indicates that society as a whole benefits from trade, there are important distributional effects, along with potential social and environmental impacts. The specific effects of trade are shaped by the social, economic and institutional context in which it operates, and impacts often represent opposite sides of the same coin. For instance, sellers are willing to export products to obtain a higher price, but removing products from the local market increases local prices and reduces local seafood availability. Conversely, buyers usually purchase less expensive seafood from distant sources, which increases seafood availability and reduces prices for consumers, but cheaper imported products then compete with local products (Asche and others, 2015). However, the net effect on affordability and broader food and nutrition security is not known.

Trade can also provide consumers with a wider set of species than what is available locally and allow producers with abundant resources and limited local markets to find buyers. Seafood is a highly heterogeneous resource, including over 1,990 wild and farmed marine species, which are used in diverse products, including fresh and frozen fillets, smoked fish and shelf-stable canned and pouch products, which are offered at a wide range of price points (Food and Agriculture Organization of the United Nations (FAO), 2024). The production of high-value marine species further incentivizes export to wealthy consumers, and correspondingly many of the top traded species groups such as salmon, shrimp and tuna are also high-value species (Gephart and others, 2024). High-value seafood exports can be particularly important for some national economies, with fisheries representing up to 80% of all exports for some island nations (Gillett, 2009). However, the distribution of economic benefits across society is context-dependent, and evidence of the impact of seafood exports on food security is mixed (Béné and others, 2010). Recent work has demonstrated that the majority (63%) of countries gain nutrient supply from trade in marine fishery products, but of the 36% of countries that experience net nutrient losses, over half are small island developing States or African nations (Nash and others, 2022).

Global seafood trade has evolved in recent decades along with shifts in global production patterns and practices. Although marine wild fish landings levelled off in the mid-1990s, total aquatic food exports nearly doubled from 1996 to 2020, with aquaculture responsible for the majority of that increase (Gephart and others, 2024). Over this period, interregional trade remained dominant for many regions, but Asia became increasingly important as a destination market for all regions. Correspondingly, there have been shifts in the top importers and exporters of marine products. For example, between 1996 and 2020, China and the Russian Federation emerged as the top two exporters of marine wild fish products (Gephart and others, 2024). However, a significant share of Chinese exports represents products imported for processing and re-exported, with China re-exporting an estimated 75% of its total aquatic food imports (Asche and others, 2022b). This pattern represents another important change in aquatic food trade: the commodification of aquatic foods and regional specialization in processing.

In the present subchapter, the focus is first on the drivers underlying increased trade. An overview of the risks to trade from both slow-moving pressures and sudden disruptions is then provided. Next, the environmental impacts associated with trade are reviewed, followed by key social and economic considerations. Lastly, key governance aspects related to trade are covered before describing sustainability pathways for marine resource trade.

2. Pressures and impacts

Drivers of increasing trade

The uneven distribution of fisheries resources and suitable production environments underpins trade, but there are a number of economic, logistical and governance factors driving increased trade in recent decades. Population and economic growth have increased demand for all types of food products. Aquatic foods play an important role in meeting this demand as global aquatic food production has increased more rapidly than the human population (FAO, 2024), with aquaculture (dominated by inland production) playing a crucial role in meeting recent and projected future demand, as the scope for increasing supply from wild fisheries is low (Costello and others, 2019; Naylor and others, 2021).

Whether and where seafood is exported depends on consumers' willingness and ability to pay, along with the presence of infrastructure to support transport to those markets. The globalization of seafood markets has been facilitated by improved logistics that reduce transportation costs, thereby increasing the competitiveness of distant producers or distant markets (Anderson and others, 2018). Lower logistics costs and improved supply chains, such as cold chains, enhance producer and consumer access to seafood markets, but such improvements have disproportionately been realized in wealthier countries. However, in recent years logistics have improved globally, and the share of seafood traded to the wealthiest countries has diminished correspondingly (Asche and others, 2015). Relatedly, a lack of local processing facilities, wage differentials and differences in regulatory stringency across nations have likely contributed to increased exports for processing and re-exports.

International governance systems have also accelerated trade. The introduction of exclusive economic zones (EEZs) extending to 200 nautical miles in the 1970s, with broader adoption in 1982 under the United Nations Convention on the Law of the Sea, excluded distant-water fishing activities from fishery access without a formal access agreement and, in many cases, the domestic fishers who assumed control continued to supply the same markets through exports. For instance, in Japan this drove the transition from a distant-water fishing nation to a major seafood importer (Swartz and others, 2010). Lastly, the Agreement Establishing the World Trade Organization (WTO), and its predecessor the General Agreement on Tariffs and Trade, regards seafood as an industrial rather than an agricultural product. This contributes to increased trade as tariffs are generally lower for industrial products, and there have been several general reductions in the maximum tariff rate in this category (Bellmann and others, 2016). There are also numerous agreements giving some countries preferential treatment in the form of lower tariffs, sometimes zero or tariff-free export quotas that have an impact on trade flows and market access (Roheim, 2004).

Slow-moving pressures on seafood trade

Although seafood trade has continued to grow in recent decades, evolving economic, regulatory and geopolitical conditions, along with changing environmental conditions, serve as pressures that inhibit and reshape trade.

Although aquatic foods are generally subject to low tariffs, many countries seek to protect domestic processing industries by escalating tariffs on products that are more processed. Aquatic food has also appeared in numerous anti-dumping cases, particularly in the European Union and the United States of America. While there may be legitimate reasons for this, there has been a significant increase in such cases in general, as well as for seafood specifically, and following the establishment of WTO, countries have limited possibilities for increasing tariffs (Asche and others, 2015). A similar situation exists for so-called non-tariff barriers. These come in a number of forms such as heightened food safety regulations, which are legitimate under the WTO Agreement as long as they are not discriminatory (Bellmann and others, 2016). However, such regulations have increasingly been used with some indication that they serve as a substitute for tariffs, sometimes as short-term measures that slow imports until a broader agreement is reached (Asche and others, 2015).

It has also become legal to implement trade measures to prevent seafood produced with what the importing country considers environmentally unacceptable production practices, as long as these are not discriminatory (Roheim and Sutinen, 2006). For instance, the United States has import restrictions on tuna with a high by-catch of swordfish, as well as on shrimp with a high by-catch of turtles. More recently, the Seafood Import Monitoring Program was implemented by the United States to combat illegal, unreported and unregulated (IUU) fishing. Similarly, the European Union has had a programme using import restrictions to combat IUU fishing since 2008 (Sumaila, 2019).

Environmental change is simultaneously shifting production, with the potential to reshape global trade. Climate change is modifying ocean biophysics and thus generating diverse ecological, economic, nutritional and social impacts (Cheung and others, 2010; Golden and others, 2016; Lam and others, 2016). Fisheries productivity is also projected to shift, with large decreases around the equator and increases in Arctic waters (Cheung and others, 2010) (for more on the climate impacts on fisheries, see sect. 4, subchap. 4D; and subsect. 5A, subchaps. 1A and 1B). Climate impacts can compound existing challenges in marine fishery production, which have already stagnated global catches, and an estimated 28–33% of all stocks are overexploited and 7–13% of stocks have collapsed (Branch and others, 2011). Changes in local fish abundance can also incentivize trade as local consumption may be maintained by increased imports and increases in fish abundance may incentivize exports. The higher degree of control in the aquaculture production process can allow it to be more climate-resilient (Asche and others, 2022a), though the impacts of climate change on marine aquaculture (mariculture) production potential are projected to be heterogeneous (Froehlich and others, 2018).

Disruptions to seafood trade

Sudden disruptions, or shocks, to seafood trade can occur due to a range of environmental, policy, economic and logistical events (Davis and others, 2020). Production shocks represent drops in landings or mariculture harvest, which can potentially reduce exports, creating a risk of the shock propagating to other countries. Theoretical work suggests that net importers, low-income nations and countries with low food stocks tend to be more exposed to the effects of such shocks, but there is limited empirical evidence of this risk (Gephart and others, 2016; Marchand and others, 2016; Tamea and others, 2016). Industrial-scale producers also have better access to more diversified markets, enabling them to avoid the impact of many shocks by reallocating their exports to alternative markets (Asche, Sogn-Grundvåg and Zhang, 2022; Straume and others, 2022). Conversely, trade also allows countries to buffer drops in their own production through increased imports. Analysis of past aquatic food production shocks suggests that exports decrease about as often as imports increase, although the exact combination is highly context-dependent (Gephart and others, 2017).

Disruptions can also occur at other points along the supply chain, including events that specifically have an impact on trade, such as those affecting transportation logistics and the implementation of trade barriers (Davis and others, 2020). As an ocean-based resource, seafood production is exposed to natural hazards that have an impact on associated infrastructure, such as tropical storms, tsunamis and flooding, which affects fishing vessels, coastal aquaculture farms and coastal ports. Disturbances create uncertainty in landings, prices and incomes that can affect actors along the supply chain from fishers to processors to wholesalers and retailers (Rice and others, 2024). Meanwhile, shipping bottlenecks and long waiting times in ports pose a risk to highly perishable products. Trade barriers, such as tariffs or import bans, which can arise from geopolitical disputes, can also restrict trade (see subsect. 5A, chap. 6). Changes to import standards can serve as an important shock for exporters, as occurred in 1997 with the import ban by the European Union on shrimp from Bangladesh based on the claim that the shrimp did not meet the hazard analysis critical control point regulations, resulting in $14.7 million of lost revenues in the processing sector (Cato and Dos Santos, 1998; Yunus, 2009).

As a notable, but potentially unique shock, the coronavirus disease (COVID-19) pandemic disrupted all stages of aquatic food supply chains, but also highlighted many forms of adaptiveness (Love and others, 2021; Nyiawung and others, 2024). For international trade, the earliest impacts were related to the ban on live animal imports by China, which, for example, halted live lobster exports to the country and increased congestion at ports due to quarantine closures (Love and others, 2021). Cancelled passenger flights also restricted trade in fresh products air-freighted in their cargo (Love and others, 2021). The closure of hotels, restaurants and cafés and decreases in tourism were also a major cause of disruption to seafood supplies in many locations (Nyiawung and others, 2024). However, in some cases, suppliers were able to adapt within the global trade network. For example, in the early months of the pandemic, frozen Ecuadorian shrimp destined for China were transferred to the United States and European markets, and Norwegian salmon destined for China was shipped to the United States and Brazil (Love and others, 2021). In other cases, suppliers provided local markets through direct selling, as was the case in many locations across the world, with small-scale fisheries producers often stepping up to provide seafood to their communities (Bassett and others, 2022; Belton and

others, 2021; Campbell and others, 2021). For more on COVID-19 impacts, see subsection 5B, chapter 7.

Environmental impacts stemming from trade

The specific impact of trade on the environment depends upon the environmental, socioeconomic and regulatory contexts. Trade can theoretically reduce environmental pressures generated by food by shifting production to regions that are more efficient, due either to superior technology or to environmental conditions (Yang and others, 2006). By shifting processing to countries with more efficient processes, trade can reduce environmental footprints by increasing product yields (see subsect. 5A, subchap. 1E). Centralized processing and access to larger markets also creates opportunities for trade to support a more circular economy by supplying by-products to markets where there are existing alternate uses (e.g. fish heads). Trade can also create opportunities for product substitution that can reduce pressure on poorly managed fisheries, as has been demonstrated for some types of aquaculture production (Asche, Oglend and Smith, 2022).

However, trade can also increase environmental impacts through three mechanisms: (a) increased global demand; (b) shifting sourcing to countries with weaker regulations; and (c) transport-related emissions. Under an open access situation for fishery resources, increased global demand coupled with trade liberalization increases fish prices, motivating increased harvesting effort by exporters. In the absence of entry restrictions or when regulations are weak, this could reduce stocks and catch in the long run, which implies negative environmental impacts from trade (Brander and Taylor, 1998). However, as a corollary, imports into a country with weak management would likely reduce prices and thereby fishing pressure. The net welfare effect will depend on the comparison between the short-run gains and the long-run losses from reduced stocks (Brander and Taylor, 1998). Recent empirical research on the impact of trade on stock status shows mixed evidence. Consistent with theoretical predictions, Eisenbarth (2022) shows that exports significantly increase fishery resource depletion. Meanwhile, Erhardt (2018) found that trade liberalization may decrease the likelihood of fishery collapse in countries with lax governance. Trade liberalization may also reshape local governance. For example, a price increase of marine resources in a given exporting country due to demand increase from trade could affect common-pool resource management (Dietz and others, 2017).

Trade liberalization has also fuelled increases in aquaculture production. Because aquaculture requires resource inputs, especially feed, and relies on natural environments, there are different areas of concern: water pollution from nutrient load and the use of antibiotics; escaped fish that could produce genetic contamination; the spread of fish disease; and pressure on other natural resources because of input demands such as feed (Asche and others, 2022a; Gephart and others, 2021). Although there is currently no clear evidence as to whether trade is driving increases in aquaculture-related environmental impacts, any incurred impacts must be weighed in the context of the broader food system (i.e. how they compare with foods that would be eaten instead) and their nutrient contribution (Gephart and Golden, 2022).

Lastly, since diet-related greenhouse gas emissions are dominated by the production stage, the question of which foods are consumed is generally more important than where the food is produced (Halpern and others, 2022; Poore and Nemecek, 2018). Aquatic foods generally result in lower greenhouse gas emissions than terrestrial animal-source foods, meaning that improved seafood availability can reduce dietary emissions when replacing higher emission foods (Gephart and others, 2021; Poore and Nemecek, 2018). Nevertheless, transport itself results in greenhouse gas emissions, as transport is responsible for around 10% of life cycle emissions for food (Poore and Nemecek, 2018). Air-freighted products, including some high-value seafood products, typically have much higher transport emissions. However, the breakdown of transport emissions along the supply chain is not sufficiently well established to compare product emissions for internationally traded and more regionally traded products. At present, emission-related environmental costs are not internalized in transportation costs, which enables less expensive trade across large distances. In future, transitioning transportation to renewable sources of energy would further reduce the overall life cycle emissions of seafood.

3. Socioeconomic considerations

Seafood trade results in a diverse set of social and economic changes, which depend on the production and institutional context. Potential impacts stemming from seafood trade generally differ for the industrial and small-scale sectors due to the larger scale and capacity of industrial aquaculture and fisheries supply chains.

Industrial fishing and mariculture production and trade can support income and livelihoods in coastal communities. Empirical evidence on the impact of export-oriented fisheries and aquaculture on local economies suggests that the effect could be significant but depends on local conditions. For example, a recent study of Alaskan fisheries indicates that positive direct effects include an increase in local employment for the fishing crew, greater added value from processed catch and a spillover effect from commercial fishing to non-fishing sectors (Watson and others, 2021). However, industrial-scale seafood production also creates many of the most significant challenges associated with seafood production when governance is weak; for example, large-scale distant-water fleets have been associated with severe overfishing and forced labour (Decker Sparks and Hasche, 2019; Nakamura and others, 2018).

Mariculture can also represent an important source of revenue, with the potential to transform coastal communities in myriad ways. An example is the salmon farming industry in Chile, currently representing around 6% of the country's total exports of goods. The rise of this industry has transformed regions where it has developed, resulting in heterogeneous impacts across local coastal communities traditionally devoted to small-scale agriculture and artisanal fisheries (Barrett and others, 2002). Developing an export-oriented seafood industry has also been important for employment and settlement along the Norwegian coast (Johansen and others, 2019). Although the empirical evidence is limited, large-scale aquaculture appears to have contributed to poverty alleviation and reduced income inequality in some remote coastal communities. For example, Ceballos and others (2018) found that industrial salmon aquaculture reduced poverty in remote coastal areas of southern Chile, while Cárdenas-Retamal and others (2021) found evidence that this industry also reduced income inequality where it operates.

In the context of small-scale fisheries, the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries, the United Nations Declaration on the Rights of Peasants, and indicator b.1 of Sustainable Development Goal 14 call for ensuring small-scale fishers' security of tenure and access to resources and markets (FAO, 2022a, 2022b). Small-scale fisheries account for at least 40% of global fish landings and although most small-scale fishery landings are marketed domestically, a substantial share of marine small-scale fishery landings enters international trade (FAO, Duke University and WorldFish, 2023). Small-scale fishers, farmers and their communities around the world, however, face barriers in accessing markets for their harvests, as they often lack sufficient marketing facilities, appropriate logistics infrastructure and technology, or access to financial services such as a bank account or credit and loan schemes (Golo and Erinosho, 2023; Kanyimba and Jonas, 2023). Financial institutions, for example, are hesitant to finance small-scale fishers because the majority do not have collateral or bank accounts (Kanyimba and Jonas, 2023). Small-scale producers can also face barriers to certification, which can limit access to potential price premiums for exported products (Stratoudakis and others, 2016; Wakamatsu and Wakamatsu, 2017). For more on small-scale fisheries, see subsection 5A, subchapter 1B.

Gender dimensions of trade

Women make up 40% of the labour force involved in small-scale fisheries-related activities (FAO, Duke University and WorldFish, 2023). They play an essential role in all aspects of the fisheries value chain (Harper and others, 2013; Pedroza-Gutiérrez and Hapke, 2022). They are engaged especially in processing and trade, as trading fish is considered a suitable activity for women in many societies (Overå, 2007; Pedroza-Gutiérrez and Hapke, 2022). However, gender norms and rules vary and while women dominate trade in some places, such as Ghana, they might not engage in fish trade in other countries, such as India and Mexico (Pedroza-Gutiérrez and Hapke, 2022).

Despite women often playing a central role in fish trade and markets, their labour is largely informal and therefore "invisible", underscoring the persistent need for gender-disaggregated statistics. Moreover, women's double burden – which involves the responsibility of managing the household and childcare (Kleiber and others, 2017; Weeratunge and others, 2010) – limits the possibility of childbearing-aged women spending more hours in the marketplace or travelling to fish markets, which affects their income. Therefore, gendered institutions in

fish markets shape trading dynamics, limiting women's participation.

The gendered nature of the fisheries sector results in women often concentrating in local small-retail trade, relegated as helpers, with limited access to wholesale fish markets where higher-income fisheries activities take place. Men often dominate larger-scale trade and benefit from a larger economic income obtained from these activities. However, despite the disadvantages for women of securing access to fish, the economic income generated by this activity represents a livelihood strategy that benefits household and local economies. Therefore, to transform existing gendered fish trade dynamics that limit women's participation, it is imperative to give voice to women in fish market governance and improve access rights to resources and training (Oloko and others, 2024).

Role in food security

Aquatic foods are highly nutritious and play a central role in food and nutrition security for billions of people (FAO, 2024; Tigchelaar and others, 2022). In many coastal countries, the majority of landings from small-scale fisheries are consumed in the household, or gifted or bartered with kin and community, thereby directly contributing to local food and nutrition security (March and Failler, 2022; Seto and others, 2024). Aquaculture production may also contribute to local and national food security (Garlock and others, 2022), although there is limited work distinguishing between inland and marine aquaculture impacts on food security.

Seafood caught or farmed for sale in local or international markets can directly or indirectly contribute to food and nutrition security. Trade can directly help to meet seafood demand in many countries (Gephart and others, 2024), and imports can be highly important for aquatic food availability (Marin and others, 2024) and provide more affordable nutrients from aquatic foods (Liu and others, 2025). Seafood can also indirectly contribute to food and nutrition security by generating income, which can be used to buy other food (Béné and others, 2015). However, at the same time, seafood trade can have negative food and nutrition impacts when highly nutritious products are exported and less nutritious food is imported (see, for example, Liverpool-Tasie and others, 2021), or when commercial fishers compete with artisanal and subsistence fishers (Belhabib and others, 2020). This may happen when farmed or wild seafood is only seen for its export value and contribution to the national economy, undervaluing its importance as a source of nutrition (Farmery and others, 2021).

Interactions and competition with other ocean-based economy sectors

In response to increased recognition of the ocean as an economic frontier, industrial-scale development has accelerated in the ocean over the past two decades (Jouffray and others, 2020). Growth in ocean-based economy sectors such as shipping and port development have created opportunities for further trade. For example, investments in the development of seaports stimulate foreign trade growth in port areas and neighbouring regions (Fedorenko and others, 2021). However, the growth of these sectors alongside other ocean-based economy sectors such as mining, energy production, tourism and marine conservation has created competition for ocean space and resources, which may constrain seafood landings and affect the livelihoods of fishers (Germond-Duret, 2022; Germond-Duret and others, 2023). Referred to as "spatial squeeze", the conflict potential between fisheries and mariculture with other ocean-based sectors is expected to increase (Stelzenmüller and others, 2022) as fisheries and aquaculture are rarely prioritized in blue economy narratives or related marine spatial planning exercises (Farmery and others, 2021).

Tourism, particularly ecotourism, contributes substantially to growth in gross domestic product (GDP) and total employment in many countries (Cisneros-Montemayor and Sumaila, 2010). Increased tourism can lead to greater domestic seafood trade to meet restaurant demand. For example, deep-bottom fish species account for a substantial component of commercial fishing income in Vanuatu, driven by tourist demand (Vanuatu Fisheries Department, 2016). Tourism can be an important driver of food systems, particularly in developing countries, where fisheries play a key role in the food and nutrition security of local communities (Degarege and Lovelock, 2020). At the same time, international trade could also supply foreign seafood products to meet tourist demand.

Without appropriate guardrails, further coastal development is likely to result in impacts on ocean ecosystems, such as physical damage to habitats, waste discharge, oil spills and noise pollution (e.g. Simpson and others, 2016), leading to degradation of wild-capture fisheries that could reduce their yield. These environmental changes, coupled with climate change, are projected to

have a negative impact on the food and nutrition security of millions of coastal people and affect trade (Golden and others, 2016; Hicks and others, 2019; Srinivasan and others, 2010). However, if done well, ocean-based economy development can produce synergies. For example, potential fishing opportunities can arise from the development of offshore wind farms (Thatcher and others, 2024) and programmes such as the Blue Ports Initiative are aimed at transforming marine ports to promote social, environmental and economic sustainability.

4. Sector-relevant governance

The impacts of the seafood trade, whether positive or negative, on local environments, economies and communities are shaped by the institutional and governance context. Each fishery, whether small-scale or industrial, can operate in very different forms with a range of governance structures. These governance entities can be seen as the formal and informal rules and norms governing fishing interactions and behaviour (Pellowe and Leslie, 2020) and shaping how benefits and externalities accrue along value chains. They create fishery management institutions, which are highly influenced by the fisheries context, and at the same time shape and are shaped by national and global market demands (Eriksson and others, 2015). Formal institutions that depend on human action, related to the State and government regulations, and informal institutions such as self-imposed codes of conduct (Van Assche and others, 2020) all govern marine fisheries around the world (Pellowe and Leslie, 2020). Depending on the context, informal institutions can promote sustainable fisheries management (e.g. Pedroza-Gutiérrez and López-Rocha, 2021) or undermine it because they can determine norms of operation that can allow unsustainable practices and illegal fishing activities (Etiegni and others, 2017). While trade can create incentives that exacerbate positive or negative features of governance, the present part of the subchapter is focused on governance and management structures directly related to trade, namely trade measures aimed at ensuring the sustainability of traded seafood and trade measures focused on ensuring positive health and social benefits.

Trade measures for ensuring the sustainability of traded seafood

Rigorous traceability and other verification systems have become increasingly important to reinforce and support sustainable aquaculture practices and fisheries management in the context of globalization. A range of bilateral and international agreements, national import regulations and private certifications have become prevalent for regulating seafood trade and supporting seafood traceability (Lewis and Boyle, 2017).

The earliest sustainability-focused trade measures for seafood targeted restricting trade in endangered species. Governments have passed laws banning or restricting trade in endangered species, including aquatic species. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international treaty under which all Parties subject species listed in CITES Appendices to additional trade controls, in compliance with CITES provisions. However, relatively few marine species fall within CITES (Vincent and others, 2014), although the set of shark and ray species included was expanded in 2023 (History of CITES Listing of Sharks (Elasmobranchii), CITES, n.d.). Bilateral and regional trade agreements can also include sustainability standards for fisheries and aquaculture products.

Import regulations aimed at restricting markets for IUU-sourced products are becoming increasingly common. IUU practices have been estimated to account for 18% of global fisheries, equating to losses in value worth $10 billion to $23.5 billion annually (Agnew and others, 2009) and reduced economic benefits of roughly $50 billion a year (Roheim and Sutinen, 2006). As a first layer to reduce market access for IUU-sourced products, the Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing, introduced in 2016, was the first binding international agreement to prevent vessels engaged in IUU fishing from using ports and landing their catches. In this way, the Agreement on Port State Measures limits the ability of IUU-sourced products from entering national and international markets. As another layer, individual countries or groups of countries have created import regulations that require reporting on seafood sourcing and/or documentation, such as the European Union catch certification programme and the United States Seafood Import Monitoring Program.

In addition to national and international regulations, a range of private labelling and certification schemes rely on traceability and chain of custody systems to ensure that seafood from certified sustainable fisheries is accurately identified and sold in the international market (Roheim and others, 2018). Early approaches to

promoting sustainable seafood supply chains are focused on single species eco-labels, such as dolphin-safe tuna, and seafood ranking guides, such as the Monterey Bay Aquarium Seafood Watch programme and Ocean Wise. Sustainability- and conservation-related certification tools such as those of the Marine Stewardship Council and the Aquaculture Stewardship Council have expanded and evolved to influence relationships between actors within the supply chain and buyers and consumers (Bush and Roheim, 2019).

Trade measures to promote positive health and social outcomes

Trade can benefit human health by providing employment opportunities, improved living conditions and improved access to nutritious food, but it can also result in harm to health and health equity (Hawkes and others, 2009). However, clear benefits can be gained by aligning trade policy so that it contributes explicitly to the goal of improving diets and nutrition. Countries such as Ghana and Samoa have attempted to do so, with mixed results (Thow and others, 2014, 2017).

Food products, including seafood, are governed by a variety of national, regional and international food safety rules, guidance and codes of practice aimed at protecting consumers from health hazards. These protections cover such issues as food hygiene, chemical contaminants and diseases and their compliance with national food standards. International standards, such as those produced through the Codex Alimentarius Commission, a joint body of FAO and the World Health Organization (WHO), are also aimed at improving the safety, quality and fairness of the international food trade. Global improvements in food and nutrition security under an open and inclusive trade regime have contributed to falling levels of undernourishment, better nutrition, greater dietary diversity and overall economic development (International Food Policy Research Institute (IFPRI), 2018).

Trade can also provide greater income security and improved labour standards that can promote positive health and social outcomes within appropriate governance structures. However, opening trade in countries without appropriate guardrails can create social risks, including those stemming from increases in inequality and negative impacts on health (IFPRI, 2018). The significant incidence of debt entrapment, human rights abuses, forced labour, child labour or forced child labour in the main seafood hub countries has led to legislative changes, making food companies liable for the working conditions behind the goods they sell (Decker Sparks and Hasche, 2019; Nakamura and others, 2018). Multilevel governance approaches are needed to deal with the potential negative effects of market integration on local livelihood options and fishery health (Crona and others, 2015).

5. Sustainability pathways

The production of seafood is unevenly distributed around the world due to differences in environmental conditions, comparative advantages and governance institutions (Smith and others, 2010), and climate change is already reshaping the distribution of seafood globally (Cheung and others, 2010). Therefore, by 2050 trade will need to play an even more important role in supporting sustainable production and equitably distributing the nutritional and economic benefits stemming from seafood production. Positive outcomes related to trade will need to be expanded in food systems, spanning from those oriented towards local sourcing, reflecting local resource endowments and capacities, to those oriented towards global sourcing.

Sustainable wild fish and mariculture production is the foundation of sustainable trade in marine foods. Appropriate management must first be in place to enable trade in sustainable products. Trade can also serve as a tool to incentivize better social and environmental performance by limiting markets for illegally caught products that create an unfair playing field, creating opportunities for higher prices for sustainably sourced products and raising the global standard for products.

However, to realize this opportunity, it is important to strengthen sustainability standards for all seafood and improve traceability systems. Under this scenario, countries need to adopt strong import regulations that are inclusive of social and environmental sustainability standards and to coordinate these standards in order to align reporting criteria and create interoperable systems that reduce the burden on industry. To ensure that higher trade standards do not impede market access for lower-income countries, countries must coordinate to support these producers in meeting import standards. This

includes equitable investments in processing technology and infrastructure.

To support the implementation of trade standards, countries could invest in tools related to traceability and environmental forensics. For example, blockchain technology provides a distributed record-keeping system to track claimed seafood product origins and movements (Blaha and Katafono, 2020). The claims include a record of actors and other information that can be used to verify claims and connect trade flows to bad actors. A key area of development is environmental forensic tools. DNA analysis, genomics and biogeochemistry allow for the identification of species, in some cases allowing subpopulations to be distinguished, testing for wild versus farmed origin, and improved estimation of geographic origin (Boultby and others, 2024; Cusa and others, 2022). Identifying the actors involved allows trade flows to be connected back to vessel information, which can subsequently be linked to production stage activities using remote sensing, satellite imagery and machine learning to detect destructive and illegal fishing activities, such as dynamite fishing and the presence of IUU fishing vessels and support systems, including bunker ships, transshipment ships and offshore infrastructure.

While these technologies are rapidly improving, they still require significant investments (Sumaila and others, 2021), and key knowledge gaps remain with respect to their broad application. The initial phase of adoption has generally involved industrial, high-value fisheries, but as technology systems improve and costs decline, broader adoption is possible. Knowledge gaps nevertheless remain with regard to equitable expansion to small-scale fisheries, and research on strategies for market development that is inclusive of small-scale fisheries remains a priority.

While ensuring the sustainability of traded seafood is important, it does not guarantee on its own that trade positively contributes to human well-being. Eliminating existing injustices related to aquatic food trade requires incorporating three interdependent dimensions of justice: distributional (economic structures enable people to have the resources necessary to fully participate), recognitional (social and cultural structures recognize all identities, allowing participation) and representational (political structures ensure voices count in decision-making) (Hicks and others, 2022; Schlosberg, 2007). There is no single tool for eliminating injustices related to trade; however, countries can take several steps towards this. First, they can develop meaningfully inclusive processes for crafting trade policies and agreements. Second, they can ensure transparency in decision-making processes for trade agreements and policies and in the monitoring of adherence to, and impacts of, adopted trade agreements and policies. As an element of improved transparency, countries can support the democratization of information, which requires clear identification of data and maintenance thereof with complete metadata, following best practices for open data. Third, if communities choose to export products, they may also aim to capture greater economic value in their communities, which could require processing and trade infrastructure and training to ensure that products meet safety and sustainability standards.

To arm communities and countries with the information needed to make decisions about trade policies, there is a need for better understanding and recognition of the diverse benefits of aquatic foods. Aquatic foods represent an economically valuable resource and are increasingly recognized for their high nutrient content and long-standing importance for livelihoods and cultural practices. Clearer pathways are needed to support the inclusion of fisheries and aquaculture in food systems planning, where the focus has been on terrestrial agricultural activities (Farmery and others, 2024). Better understanding of the diverse values of seafood, combined with inclusive decision-making processes, will enable seafood trade to better contribute to the range of social, environmental and health goals.

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Chapter 2
Recreational fishing

Key points

- Marine recreational fishing is a widely practised activity with substantial economic and ecological impacts, especially on coastal ecosystems. Marine recreational fisheries generate billions of dollars annually, particularly in developed nations. The fact that many marine recreational fisheries are not formally recognized creates governance challenges for sustainability.
- Effective management requires addressing data gaps for data-driven management, including integration of socioeconomic factors, fostering stakeholder collaboration and implementing equity-focused management frameworks and integrated governance, and promoting stewardship and compliance through education.

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1. Introduction

Recreational fishing, defined as fishing of aquatic animals (mainly fish) that do not constitute the individual's primary resource to meet basic nutritional needs and are not generally sold or otherwise traded on export, domestic or black markets (Food and Agriculture Organization of the United Nations (FAO), 2012), takes place in about three quarters of the world's exclusive economic zones (EEZs) (Mora and others, 2009). Globally, an estimated 300 million people participate in recreational fishing each year, generating at least $47 billion in expenditure (Arlinghaus and others, 2019; Cisneros-Montemayor and Sumaila, 2010). Many recreational fishers engage in both freshwater and marine recreational fisheries, which makes it challenging to estimate the number of marine recreational fishers. One estimate suggests that 121 million people worldwide participate in marine-based recreational fishing (Cisneros-Montemayor and Sumaila, 2010).

Rates of participation in recreational fishing in countries with reliable statistics average around 10%, translating to approximately 140 million anglers in North America, Europe and Oceania alone (Arlinghaus and others, 2015). However, participation rates do vary significantly by country. More than 40% of Norwegians (Arlinghaus and others, 2015) and 21% of Australians (Moore and others, 2023) engage in recreational fishing, primarily marine fishing. Other countries, such as Brazil, report lower participation rates (about 1%) (Freire and others, 2016), but these lower numbers are likely to be influenced by data gaps on recreational fisheries (FAO, 2012). Recreational fishing is the fastest-growing fishing subsector in China (Ding and others, 2021). Similar trends have been observed in other developing countries in Asia and Africa (Kadagi and Wambiji, 2021), brought about by changing social norms, economic development and tourism (Coleman and others, 2004; Cooke and Cowx, 2004).

The focus of the present chapter is on marine rather than freshwater recreational fisheries. Integrating marine recreational fisheries into marine fisheries conservation and management is important owing to the ecological impacts of excessive recreational harvest (Altieri and others, 2012; Lewin and others, 2006, 2019), but also in view of the significant social and economic benefits that such fisheries bring to communities and participants (Hyder and others, 2018). Marine recreational fisheries support employment in retail, boating, tourism and related sectors, and offer public health benefits by encouraging outdoor activities and supporting nutritional security (Cooke and others, 2018; Henry and Lyle, 2003). In some coastal areas, the economic value of recreational fisheries exceeds that of small-scale commercial fisheries (Strehlow and others, 2023). The value of recreational fisheries for individual participants, however, lies in psychosocial benefits, relaxation and access to self-caught fish (Parkkila and others, 2010) . Furthermore, marine recreational fisheries foster awareness about conservation issues, strengthening the connection between fishers and marine ecosystems (Barnett and others, 2016) and promoting broader stewardship efforts (Shephard and others, 2023, 2024). The socioeconomic and ecological significance of recreational fishing underscores the need for sustainable and scientifically informed management practices in marine environments that take into account the needs, impacts and socioeconomic importance of marine recreational fisheries (Cowx and others, 2010; Hyder and others, 2018, 2020).

Certain marine and coastal aquatic species are exploited either solely by recreational fishers or by both recreational fishers and commercial and customary fisheries (Arlinghaus and others, 2019, 2023; Hyder and others, 2018; Ihde and others, 2011; Mora and others, 2009). Given the large number of people engaged in marine recreational fisheries, the impacts are diverse and include: (a) potentially high harvest rates of fish and other animals, which can reduce population abundance; (b) selective removal of specific species, sizes and genotypes, leading to truncated age and size structures and potential trophic cascades that may affect ecosystem stability, ecological interactions, genetic diversity and adaptive potential; (c) habitat modification and disturbance as a result of trampling, boating, anchoring and bait collection; (d) pollution from lost or discarded fishing gear; and (e) the introduction of invasive species via bait transfer (Lewin and others, 2006, 2019). As these impacts vary by location and fishery, local evidence is necessary to better understand the relative importance and consequences of these pressures.

Recreational fisheries are by no means the only source of impact on coastal fish populations. In fact, although comprehensive global assessments are limited, evidence suggests that marine fish populations are generally more heavily affected by industrial commercial fisheries than by recreational fisheries. However, the populations of specific coastal species that are easily targeted may be predominantly harvested by recreational fishers

(Altieri and others, 2012; Kleiven and others, 2016). In some cases, such as in Australia and the United States of America, recreational fisheries contribute up to 100% of the harvest for specific coastal fish populations (Coleman and others, 2004; Tracey and Stark, 2024).

As the economic situation improves in many countries, motivations for recreational fishing are shifting from food provision to leisure and experience (Kleiven and others, 2020). These non-catch benefits (e.g. enjoying nature) mean that recreational fishing effort often remains steady despite declining fish populations, unlike fishing effort in commercial fisheries, which often correlates with stock levels and expected gains (Kleiven and others, 2020; Post and others, 2002). Recreational fishing effort surged in many regions during the coronavirus disease (COVID-19) pandemic, though the long-term sustainability of this increase is uncertain (Audzijonyte and others, 2023; Britton and others, 2023; Kaz and others, 2024).

Despite the popularity of marine recreational fishing, reporting marine recreational catch is not required in most countries, with the exception of certain specific species or regions (Coleman and others, 2004). In Brazil, tournament catches must be reported, but compliance remains low. The European Union recently mandated marine recreational catch reporting, though implementation across member States will take years. Consequently, estimates of total marine recreational catches and harvests are highly uncertain. The global Sea Around Us project (Freire and others, 2020) estimates global marine recreational landings at over 900,000 tons in 2014. Independent estimates suggest annual removals of around 200,000 to 300,000 tons in the United States (Andrews and others, 2018; Cooke and Cowx, 2004), 350,000 tons in the European Union (Hyder and others, 2018), and some 25,000 to 30,000 tons in Australia (Henry and Lyle, 2003) and New Zealand (Southwick and others, 2018). The actual catch from recreational fishing is likely to be much higher as some fish are caught and released (Coggins and others, 2007), and the impacts of post-release stress and mortality are likely a significant cause of unaccounted mortality in some fisheries (Cooke and Suski, 2005).

Catch and release is widely practised: it is estimated that, worldwide, 60% of recreational catches are released (Cooke and Cowx, 2004), although estimates range widely based on country, fishery and species (Ferter and others, 2013; Lennox and others, 2017). Fishers catch and release either in order to comply with management regulations, such as bag or size limits, or simply by choice, releasing a fish that could be legally harvested (Ferter and others, 2013). The impact of catch-and-release practices is complex, and post-release mortality varies across species depending on factors such as water depth, gear used, fisher behaviour, fish handling times, water temperatures and species biology (Brownscombe and others, 2017). In addition to direct post-release mortality and barotrauma injuries — which are particularly relevant in deep marine environments — other potential negative impacts of catch and release include hook-related injuries, effects on growth and reproduction, increased predation risk after release, and reduced reproductive success if fish are caught and released during reproductive activities (Arlinghaus and others, 2007). In certain contexts, such as fishing at great depths or in areas with high predation pressure, post-release mortality rates can be extremely high, raising ethical concerns about whether releasing fish could be considered "wasting" fish (Coggins and others, 2007).

As reliance on fishing for food diminishes in more developed nations as a result of changes in the management of recreational fisheries and social norms, release rates are likely to further rise in cultures in which the practice is perceived as a conservation measure that reduces mortality. Alternatively, release rates may decrease where catch and release is viewed as an unethical practice, akin to playing with animals without a purpose — a perspective held in certain individuals and cultures, as in Germany and Switzerland (Arlinghaus and others, 2012). In these countries, only fishing for food is considered morally acceptable, and indeed the primary motivation in many countries for catching fish is for food (e.g. Atlantic cod, *Gadus morhua*) (Bronnmann and others, 2023).

Beyond the direct impacts of harvesting and catch-and-release fishing, recreational fishers are often highly selective, targeting the largest specimens and predatory fish (Flink and others, 2024; Lewin and others, 2006). They also disproportionately remove more active and bolder fish (Biro and Post, 2008; Klefoth and others, 2017; Sbragaglia and others, 2024), which may have higher reproductive success and adaptive potential (Sutter and others, 2012). The removal of predatory species based on size and other traits can affect ecosystem trophic structure by changing natural species composition and reducing predatory control (Lewin and others, 2019).

2. Pressures

Over the past decade, changes in the impacts of marine recreational fisheries on ecosystems and fish populations have been driven primarily by: (a) a growing human population, especially in coastal areas (about 15% of the global population currently lives within 10 km of a coast) (Cosby and others, 2024); (b) rapid advances in gear and technology, allowing recreational fishers to detect and target specific species, gain access to previously unreachable areas and use increasingly effective lures and baits (Cooke and others, 2021); and (c) the rise in communication technologies, which facilitate rapid information exchange and are shifting societal norms, with both positive and negative effects on marine ecosystems (Cooke and others, 2021). While the total global estimated marine recreational harvest constitutes only about 1% of total commercial landings, recreational removals are generally concentrated, and its impacts most intense, in narrow bands of coastal areas (Coleman and others, 2004). Given the potential environmental impact of recreational fisheries, sustainability is a growing concern (Lewin and others, 2006, 2019). Sustainable practices involve not only ecological but also social and governance-related issues (Coleman and others, 2004; Cooke and Cowx, 2004; Grati and others, 2024).

The cumulative impacts of recreational fishers on marine habitats extend beyond fish harvest and include disturbances from boating, anchoring and shore-based activities. In Australia, for example, there are 900,000 recreational vessels, which is 50 times the number of artisanal and industrial vessels combined.[1] That level of boat ownership is not uncommon in developed countries. Boating activity, including anchor deployment and propellor wash, can locally impact habitats such as reef systems and seagrass beds, though global impacts remain relatively low (Lewin and others, 2019). Shore-based fishing and land-based bait collection can degrade the fragile habitats in which these activities are performed intensely (Lewin and others, 2006).

As is the case for all fisheries, some fishing gear is lost during marine recreational fishing, contributing to the abandoned, lost or otherwise discarded fishing gear problem (Watson and others, 2022a). Overall, the impacts of abandoned, lost or otherwise discarded fishing gear from marine recreational fisheries are considered relatively small when compared with commercial fishing activities as the gear itself is generally small and is not routinely lost (Bornt and others, 2023; Lewin and others, 2019).

As recreational fishing remains largely unreported and, in many cases, unregulated, it is often overlooked as a component of global fisheries (Arlinghaus and others, 2019). Common regulations include licensing, gear restrictions, spatial and temporal closures, daily catch limits and size limits. However, total effort and harvest are rarely restricted at the population level, and less popular species often have no size or catch limits. Compliance monitoring is often challenging, especially in remote areas or where recreational fishing effort is relatively low and dispersed, and many recreational fishers may not even be aware of regulatory requirements (Freire and others, 2012; Ryan and others, 2025; Venerus and Cedrola, 2017).

To summarize, key sustainability challenges in recreational fisheries include declines in biomass, truncations in fish size and age through harvest, and intensified local fishing efforts that can threaten biodiversity and fish populations and, in extreme cases, lead to trophic cascades (Altieri and others, 2012). Other challenges include the introduction of non-native species via recreational gear, the lack of consideration of recreational fisheries in marine spatial planning and fisheries management (Arlinghaus and others, 2023; Hyder and others, 2018; Ihde and others, 2011) and the difficulties of obtaining data required for sustainable management, such as those on recreational catch and discards (Cowx and others, 2010; Garibaldi, 2012; Karachle and others, 2020).

Perhaps one of the greatest overarching pressures on marine recreational fisheries that incorporates all of the factors identified above is the shared utilization of coastal regions and the ecosystems and resources that they encompass (Barbier and others, 2011; Navarro and others, 2022; Noble and others, 2019). This theme is consistent with the findings of several other chapters in the present *Assessment* and is explored further from a marine recreational fisheries perspective below, under the heading “sustainability pathways”.

[1] See https://bia.org.au/wp-content/uploads/State-of-Industry-Report-2024.pdf.

3. Socioeconomic considerations

Recreational fishing generates extensive social and economic benefits on multiple scales, from individual participants to communities, regions and nations (Parkkila and others, 2010). The concept of value is interpreted variably across disciplines, with Parkkila and others (2010) identifying the psychological, social and economic impacts of fishing, distinguishing between individual benefits (e.g. angler satisfaction or health) and broader economic effects (e.g. regional tourism expenditure). In microeconomic terms, the value of recreational fishing for individuals is often measured as willingness to pay to participate. Meta-analyses have revealed high individual willingness to pay in marine recreational fisheries, with thousands of dollars generated from a single charter trip (Johnston and others, 2006; Whitehead and others, 2013). Recent estimates suggest a total willingness to pay of $11.4 billion for European recreational fisheries alone (Gren and Marbuah, 2024). While willingness to pay can quantify some of these benefits, many psychological and social values are difficult to measure (Parkkila and others, 2010). Recreational fishers often engage in environmental stewardship (e.g. coastal clean-ups or habitat restoration), participate in management councils or donate tournament catches to charity. Valuing these societal contributions is not straightforward and is rarely done quantitatively.

A macroeconomic perspective focuses on the economic impact, specifically jobs created through recreational fisher expenditures, which are particularly valuable in coastal regions reliant on tourism. In Europe, marine recreational fisheries contribute €10.5 billion and 100,000 jobs, while in the United States, they support $138 billion in sales and 692,000 jobs (Hyder and others, 2018; National Marine Fisheries Service (NMFS), 2024). In Brazil, between 2011 and 2014, marine recreational fishers spent $524 million annually (Freire and Sumaila, 2019). These benefits support local and national economies, especially in rural and coastal areas, through job creation in boat and vehicle manufacturing, fishing tackle, outfitting and tourism industries. The magnitude of the financial benefits generated by recreational fishers can be significant, at times exceeding commercial fishing revenues for certain stocks (Oinonen and others, 2016; Scheufele and Pascoe, 2022; Strehlow and others, 2023).

However, comparisons between the contributions of recreational and commercial fisheries are difficult and require examining producer and consumer surplus rather than changes in macroeconomic variables (Scheufele and Pascoe, 2022). Much of the value of recreational fishing is classified as non-market as it is derived from the fishing experience itself, which is not reflected in market prices. Some of this value can be estimated or inferred through travel cost methods, contingent valuation or choice experiments. Long-standing and well-managed recreational fisheries help to preserve local cultures and traditions, support regional economies and support fishers transitioning from non-profitable commercial fisheries. At the same time, in some countries, recreational fisheries that attract tourist trade often face the prospect of foreign ownership, limiting local economic benefits to local communities (Potts and others, 2022).

For effective consideration of socioeconomics in policy on recreational fisheries, studies must consider how the recreational fishery provides economic benefits to communities where the activity is taking place (Potts and others, 2020). Traditionally, particularly in underdeveloped communities, most of the money spent by recreational fishers is not retained in the local economy. For example, Butler and others (2020) found that the local community retained less than 10% of the money that foreign recreational fishing tourists spent at a lodge in Angola. When this economic leakage was considered, it was found that the community obtained greater economic benefits if the fish was captured in the artisanal fishery. Similarly, Potts and others (2022) found that less than 10% of the money generated by recreational fishing was retained in low-income households in a South African recreational fishery. They suggested that a whole-of-government approach, which included the identification of hotspots for recreational fisheries tourism, the development of local education and skills, and investment in appropriate infrastructure through public-private partnerships, would be necessary to realize the potential of recreational fisheries to drive social development.

In addition to having limited economic benefits, tourist-based recreational fishing ventures can clash with local communities and small-scale and subsistence fisheries. In such scenarios it is important to consider the cultural, spiritual, economic and nutritional benefits of fisheries to local communities. In the case of Indigenous Peoples that engage in ceremonial or subsistence fishing, they must be viewed as rights holders with priority access to fisheries resources. The boundary between recreational and subsistence fishing can, however, be blurred (Nyboer

and others, 2022). Given the need to manage fisheries in a cohesive and comprehensive manner, it is essential that fisheries planning extend across sectors and consider not just fish populations and fishery dynamics but also cultural traditions and values, as well as sovereign rights to fish, involving fishers as active participants in decision-making (e.g. via co-management) (Arlinghaus and others, 2016; Cooke and others, 2023).

From a demographic perspective, recreational fishing is often male-dominated and of limited ethnic diversity, and generally has a higher proportion of older participants (Arlinghaus and others, 2021; Moore and others, 2023). The reasons for that skew are unclear and may include barriers related to socialization (Arlinghaus, 2024). Some recreational fisheries tend to be limited to those with high disposable income given high entry costs, such as the purchase of a boat and the purchase of fuel, and fisheries targeting large pelagic species, such as tuna or billfish, are one of the most expensive ventures. By contrast, lower-cost shore-based coastal fisheries attract participants from lower socioeconomic backgrounds who often rely on catch to supplement protein consumption (Cooke and others, 2018). Disability inclusion in marine recreational fisheries is less understood (Lindsay and others, 2022). There are marine recreational fishery programmes that support recovery from mental health issues and rehabilitation of offenders (Bennett and others, 2017). Ensuring equitable participation remains an opportunity to enhance diversity within the sector.

There is increasing recognition that recreational fisheries must be studied and managed as coupled socioecological systems (Arlinghaus and others, 2017; Kleisner and others, 2022; Solomon and others, 2020). For example, increasing societal concerns about animal welfare resulted in bans on voluntary catch-and-release practices in Germany and Switzerland. Recreational fishing must therefore foster its social licence by meeting ethical standards, respecting animal welfare, adopting high sustainability and welfare standards (Brownscombe and others, 2017) and demonstrating environmental responsibility (Arlinghaus and others, 2012, 2021).

Community concerns about recreational fishing may also arise from conflicts with other water users, such as swimmers at a beach, for instance when vessel captains do not adhere to no wake zones. Increased marine traffic and the overall utilization of ocean space are matters of growing concern that must be resolved with adequate spatial planning. Marine spatial planning is a process aimed at reducing conflict and managing ocean space in line with economic, social and environmental objectives. Zoning frameworks support this goal in some instances, such as the Great Barrier Reef Marine Park in Australia, where zonation is aimed at balancing recreational fishing with commercial activities, diving and research (Stephenson and others, 2023). Such zonation can mitigate some user conflicts but may restrict recreational fisher access, creating further conflict. This problem is most acute in nearshore environments, where there are various forms of recreation, vessel traffic and coastal development. Managing relationships with other users and addressing conflicts over shared water resources will be critical as coastal populations grow and coastal development increases (Ramadhan and others, 2022).

Figure I
A young recreational fisher in Australia



Source: Sean Tracey.

4. Sector-relevant governance

The recreational fishing sector's lack of formal recognition is a fundamental concern in fisheries resource governance (Arlinghaus and others, 2019; Grati and others, 2024; Hyder and others, 2020; Potts and others, 2020), contributing to overexploitation (Cooke and Cowx, 2004), conflicts with commercial and subsistence fishers (Gómez and others, 2021; Kadagi and others, 2021; Said and others, 2018) and reduced societal benefits from recreational fisheries (Grati and others, 2024). Despite its importance, only about two thirds of countries mention marine recreational fishing in primary fisheries legislation (Potts and others, 2020). Barriers to recognition include limited data on recreational fishing participation, catches, biological impacts and socioeconomic importance, as well as a historical bias favouring commercial fisheries (e.g. the European Union Common Fisheries Policy) (Grati and others, 2024). Where economic value and impact data exist, efforts to compare these metrics with other fisheries often face stakeholder resistance, complicating resource allocation. Even among countries that recognize recreational fisheries, definitions are often unclear or insufficient for legal and management purposes, making it difficult to distinguish between recreational and other small-scale fisheries. Recreational fishers range from affluent, specialized touristic fishers to poorer individuals dependent on fishing for basic nutrition (Cooke and others, 2018; Nyboer and others, 2022), underscoring the need for locally adapted definitions. In some cases, there is a blurred boundary between "recreational" and "traditional" fishers given that the former could represent remnants of what was formerly a commercial small-scale sector. A case in point is the Mediterranean, where a number of individuals from fishing families have resorted to recreational licences to maintain the family tradition because fishing capacity regulations were pushing small enterprises out of business (Said and others, 2018).

The lack of data on marine recreational catch and effort and the misalignment of existing data with monitoring and reporting scales across jurisdictions make it difficult to integrate recreational fisheries data into stock assessments and management frameworks (International Council for the Exploration of the Sea (ICES), 2024). There are, however, some emerging examples of integration at various scales (Carruthers and others, 2014; Punt and others, 2020). This challenge is particularly pressing for those stocks for which recreational fishing is a significant cause of mortality (Griffiths and Fay, 2015).

Assessment methods are chosen on the basis of data availability, from data-poor (catch, effort, length) to data-rich (catch, abundance index, age/length composition) (Hoyle and others, 2024; Kokkalis and others, 2024; Rudd and others, 2021). Methods for the integration of data on marine recreational fisheries include catch-only models for species such as Baltic northern pike (*Esox lucius*) and Norway lobster (*Nephrops norvegicus*) (van Gemert and others, 2022; Zimmermann and others, 2021) and integrated models for snapper and grouper stocks (Williams and Shertzer, 2024) and European sea bass (*Dicentrarchus labrax*) (Walker and others, 2020), with some models factoring in environmental variability (Watson and others, 2022b).

Incorporating marine recreational fisheries data into stock assessments helps to refine the determination of the total allowable catch, which guides sustainable harvest strategies (Fowler and others, 2023; Harford and others, 2021) and allocation among sectors (National Academies of Sciences, Engineering and Medicine, 2024). In addition, management strategy evaluation can be used to explore how regulatory changes, such as hook size, minimum length and harvest slot limits, affect recreational harvests, as was done for the red snapper in the Gulf of Mexico (Bohaboy and others, 2022; Garner and others, 2020). In some jurisdictions, fisheries legislation takes into account biological, social and economic factors, prioritizing sustainable yields, equitable catch allocation and socioeconomic benefits (Tidbury and others, 2021), as exemplified by European sea bass management (Cevenini and others, 2023).

In the European Union, the data-collection framework now requires some marine recreational fisheries data, with specific quota allocations (e.g. for bluefin tuna) and bag limits (e.g. for dolphinfish). However, the Common Fisheries Policy's focus on commercial objectives, such as maximum sustainable yield, does not align well with recreational fisheries (Grati and others, 2024), the aim of which is often to maximize fisher satisfaction, which may require maintaining biomass levels above those typically associated with maximum sustainable yield (Birdsong and others, 2021; Johnston and others, 2010). Harmonized objectives that recognize the social and experiential goals of recreational fisheries are therefore essential for effective management (Grati and others, 2024).

Tensions are common in fisheries that are targeted by both the recreational and commercial sectors, especially

in cases where stocks are declining. In some countries (e.g. Australia, New Zealand and the United States), "explicit allocation" of catch shares — assigning fixed portions of total allowable catch based on historical data — can mitigate conflicts, but the use of historical data may also create conflict if either sector is in a growth phase or the historical representation of recreational catch share is inaccurate (Bess and Rallapudi, 2007; McShane and others, 2021). Elsewhere, allocation is implicit, with management measures indirectly influencing catch distribution. This lack of transparency can hinder balanced societal benefits, as seen with European species such as sea bass and western Baltic cod (Hyder and others, 2020). A transparent and consistent approach to explicitly allocating catch shares to recreational and commercial fisheries, taking into account both social and economic objectives and benefits, is necessary (Hyder and others, 2020), but currently not in place in most countries. Socioecological systems perspectives and economic valuation can be used to implement such an approach and have been applied to some recreational fisheries (Arlinghaus and others, 2017). Adaptive approaches are flexible and involve stakeholders rather than being top-down, but there are challenges in representing socioecological feedback processes and external drivers of changes that are beyond the control of fisheries managers. Other constraints to implementing an adaptive governance framework involve defining and representing multiple objectives that account for social, ecological and economic factors and that go beyond traditional objectives, such as maximum sustainable yield or fisheries reference points – for example, if objectives were to focus on maximizing the economic value of all sectors of fisheries instead of just maximum sustainable yield, and related fisheries reference points (Arlinghaus and others, 2019). However, establishing such systems would place even greater demands on data. It would also involve difficult negotiations about objectives and performance criteria, which are well beyond the current capabilities of most fisheries governance systems.

Only about one third of national fisheries policies support co-management in recreational fisheries, which is essential for stakeholder collaboration, sustainable resource use, compliance and local knowledge integration (Ehrlich and others, 2023; Potts and others, 2020). Co-management is challenging in recreational fisheries due to the diversity and fragmented organization of recreational fishers. Angler management organizations can facilitate stakeholder integration in management processes by sharing management responsibilities and fostering outreach (Arlinghaus and others, 2019), especially if they are broadly representative and independently funded.

Whatever mechanism is applied to manage recreational fisheries, success depends on minimizing non-compliance (Battista and others, 2018). Non-compliance may be unintentional or intentional. Marine recreational fisheries regulations vary widely, from permit systems to spatial and temporal closures. Compliance is a critical determinant of regulatory success, though only 11% of surveyed countries reported effective compliance (Potts and others, 2020). Non-compliance is challenging to estimate as it requires data from within regulatory frameworks, often collected through covert operations (Ban and others, 2022; Bova and others, 2024). Many jurisdictions have implemented enforcement programmes and legal frameworks with punitive measures to address non-compliance (Moutopoulos and others, 2020). Since these approaches have not been universally effective (Bova and others, 2024), there is growing recognition that normative approaches may be more suitable and cost-effective for regulating deliberate non-compliance and improved education for addressing unintentional non-compliance (Arlinghaus and others, 2010, 2012; Bova and others, 2017; Mackay and others, 2018).

Normative approaches may prove to be more effective and cost-efficient to regulate all non-compliance when compared with punitive measures (Bova and others, 2017; Mackay and others, 2018). Many jurisdictions are launching education and awareness campaigns to improve fishers' knowledge and support for fisheries regulations (Lindley and Quinn, 2023), and sector-led stewardship initiatives are also becoming more common. Social norms and networks significantly influence fisher behaviour and can promote accountability and sustainable recreational fishing, whereby fishers accept the need and value of managing their own catch (Arlinghaus and others, 2010, 2012; Cooke and others, 2019). Social dynamics, especially within organized clubs, on social media and through ambassadors, drive adherence to sustainable practices. Recalibration of social norms through word of mouth and social media networks can be highly effective (Allison and others, 2023), particularly if those who are sharing the message are highly respected among the target audience. When existing social norms are unsustainable or additional information (i.e. scientific evidence) suggests a need for change, localized interventions that leverage normative

influence have the potential to incentivize behavioural change and seed new norms (Allison and others, 2023; Bova and others, 2017; Danylchuk and others, 2018; Mackay and others, 2018).

Effective examples of educating fishers on best practices to account for post-release mortality include programmes such as Keep Fish Wet (Danylchuk and others, 2018) and Tuna Champions (Tracey and others, 2023), developed collaboratively by scientists, managers and angling leaders. Other efforts have focused on habitat restoration (e.g. OzFish)[2] and broader sector-led contribution to sustainable fisheries (Black, 2023). Once a critical majority has adopted the desired behaviour, social dynamics and pressures (e.g. interpersonal communication, modelling) can trigger widespread shifts, eventually tipping fisheries towards more sustainable outcomes (Tracey and others, 2023).

5. Sustainability pathways

Marine recreational fisheries are intrinsically linked to ecological assets in the marine ecosystem as fish abundance is closely tied to habitats that are affected by aquaculture, commercial fishing, marine parks, port activities, shipping and offshore energy infrastructure (Laubenstein and others, 2023; Turschwell and others, 2022). As interest grows in the blue ocean economy, with both its potential impacts and benefits for recreational fishing (Stephenson and Hobday, 2024), future marine governance will require integrated planning across multiple sectors, agencies and jurisdictions (Kidd and others, 2020; Stephenson and Hobday, 2024; Zaucha and Gee, 2019). In the lead-up to 2030 and beyond, recognizing diverse stakeholder needs, including those of marine recreational fishers, is essential for effective marine spatial planning, particularly in the recreational fishing sector, which offers substantial cultural, social and economic benefits (Hyder and others, 2020) as well as health, well-being and food security advantages (Curran and others, 2023). Integrating recreational fishing into marine spatial planning frameworks would promote social equity and acknowledge its interconnectedness with tourism and conservation (Noble and others, 2019; Voyer and others, 2017). That process starts by acknowledging that marine recreational fishers are important stakeholders with a seat at the table and that their benefits extend well beyond just leisure (Arlinghaus and others, 2019; Grati and others, 2024). Engaging stakeholders through public consultations, advisory committees and workshops ensures that fishers' unique perspectives are considered, which will ultimately lead to effective zoning and other regulations that support responsible practices (Bonsu and others, 2024). This collaborative approach fosters sustainability in marine ecosystems and encourages stewardship among recreational fishers (Ehrlich and others, 2023), and should be a priority for implementation in order to successfully achieve more sustainable oceans by 2050 (Kelly and others, 2022). Implementation will require not only significant change through transformative global governance and political will but also an understanding of the values of recreational fishing beyond economic return (Arlinghaus and others, 2019; Grati and others, 2024).

As marine recreational fisheries typically occur alongside commercial fisheries, there is a critical need for robust data on recreational fisheries to support sustainable practices and sector access (Bess and Rallapudi, 2007; MacKenzie and Cox, 2013b; National Academies of Sciences, Engineering and Medicine, 2021). Unlike for commercial fisheries, mandatory reporting for recreational fishing is rare. Most surveys are voluntary and have a vital role in informing fisheries assessments and management (Fisheries and Oceans Canada (DFO), 2015; Ryan and others, 2016, 2019; Tracey and others, 2022). Survey sampling methods should be probability-based and designed to minimize uncertainty and biases, making the data suitable for broader inferences (Sparrevohn and Storr-Paulsen, 2012; Vølstad and others, 2011). However, survey errors from declining response rates and lower landline usage pose challenges (Bova and others, 2018; Teixeira and others, 2016). Addressing these challenges and increasing the recreational fisher's self-motivation to provide data are critical to maintaining data quality and reliability (Lewin and others, 2023).

Technological innovations are essential for improving data collection and promoting sustainable fishing practices (Cooke and others, 2021; Lennox and others, 2022). Global navigation satellite system-enabled devices and digital platforms, such as mobile apps and social media, allow fishers to record their activities in near real time, providing data on fishing effort, catch, species distribution, environmental conditions and habitat quality

[2] See https://ozfish.org.au.

(Bradley and others, 2019; Venturelli and others, 2017). These tools support data accuracy, reduce biases (Crandall and others, 2018; Johnston and others, 2021) and facilitate the sharing of information on fishing regulations, conservation initiatives and responsible fishing practices. Successfully realizing the potential of technology platforms to accurately and precisely record and collate recreational catch and effort data by 2030 will be essential to effective stock assessment and appropriate and recognized resource-sharing, through either direct sector allocations or more dynamic management mechanisms, which may be just over the horizon (Venturelli and others, 2017). By 2050, all sources of mortality will need to be identified, and communities and sectors will need to understand and accept their impacts and the role that they play in maintaining and fostering a vibrant ocean (Bennett and others, 2018; Kelly and others, 2022; Mathevet and others, 2018).

Advanced technologies, such as remote cameras, computer vision and aerial and underwater drones, further enable in-situ monitoring of fishing activities, species populations and habitats. These innovations allow for the assessment of fishing pressure and fish behaviour patterns, which can be integrated into existing monitoring programmes (Flynn and others, 2018; Hartill and others, 2020; Lennox and others, 2022; Signaroli and others, 2024). At the same time, digital reporting methods require survey errors to be evaluated and non-probability sampling biases to be addressed in order to ensure representative and unbiased data collection (Gundelund and others, 2021).

Novel survey designs and statistical approaches, including probability sampling, are being developed to improve data quality and reduce costs (Ferter and others, 2023; Sande and others, 2022). The integration of these technologies into monitoring programmes is supported by appropriate governance frameworks for data collection, storage and dissemination, fostering responsible fishing and data-driven conservation efforts (Andrachuk and others, 2019; Johnson and others, 2021).

As the recreational fishing community is large, harnessing the power of people through a scientific-community-accepted, output-focused "citizen science" programme should be a priority in the lead-up to 2030 (Gundelund and others, 2020; Kelly and others, 2022; Whyte and others, 2024). Focus should be placed on how to collect data that are of use and relevance to the successful management of marine resources (Arlinghaus and others, 2019; MacKenzie and Cox, 2013a). The active involvement of fishers is essential for collecting data on and monitoring marine recreational fisheries. Effective data collection requires frameworks that support fisher engagement, encouraging individuals to share fishing activity data with researchers, who then provide aggregated insights back to the community (Ison and others, 2024). Data collected can be informative and can be used as the basis for, or as a supplement to, a range of scientific studies (Graba-Landry and others, 2023; Stuart-Smith and others, 2018). Increased engagement between researchers and fishers — "inform", "consult", "involve", "collaborate" and "empower" — enhances fisheries management by fostering a cooperative approach between management and research agencies and fishing communities (Johnston and others, 2024; Mason and others, 2017). This involvement improves stewardship, promotes responsible fishing practices and supports conservation efforts (Pita and others, 2020; Shephard and others, 2023). Integrating local knowledge with scientific methods offers a more holistic approach to fisheries management, enabling adaptive frameworks that respond effectively to fish population changes and marine spatial planning needs (Chollett and others, 2022).

Transdisciplinary governance, whereby fishers, scientists and policymakers co-develop solutions, has facilitated practical approaches to fisheries management (Said and others, 2018). Such collaboration also builds community resilience, supporting sustainable fisheries and healthy ecosystems. Recognizing the impact of habitat degradation on fisheries productivity, communities worldwide have initiated habitat restoration projects, including seagrass (Adams and others, 2024; Orth and others, 2020) and oyster reefs (Crawford and others, 2020; Gillies and others, 2020). These efforts align with the United Nations Decade on Ecosystem Restoration (2021–2030), under which the restoration of coastal and ocean habitats that are vital for fisheries and tourism sectors is prioritized (Waltham and others, 2020; Young and Schwartz, 2019).

6. Conclusions

Marine recreational fishing is a popular activity performed within a large fraction of the world's EEZs, with significant economic and ecological implications, particularly for coastal ecosystems. Marine recreational fisheries generate billions annually, especially in developed countries, supporting local communities through job creation and encouraging marine stewardship. Despite these benefits, marine recreational fishers are not considered key stakeholders everywhere and the activity itself raises sustainability concerns in connection with overfishing, catch-and-release mortality, habitat disturbance, pollution and invasive species introduction, as well as conflicts with other fisheries sectors and conservation groups. The rising fishing pressure, fuelled by technological advancements and urbanization, often lacks effective regulation, recreational fishing might pressure stocks already declining from commercial fishing and there is a lack of comprehensive data reporting and regulation, especially in remote areas.

Ecosystem-based fisheries management and marine spatial planning are aimed at balancing the needs of recreational and commercial fishing sectors and other interests (e.g. conservation) while promoting sustainable practices. These frameworks emphasize data reliability, transparent catch allocation and fishing regulations such as spatial closures, but also concerns about equity, access and infrastructure. In many areas, existing management systems have been developed for commercial fisheries, meaning that recreational fisheries can be at best inappropriately regulated and at worst marginalized. There is a need for global governance systems that consider the objectives and benefits of all sectors involved in fishing, including marine recreational fisheries, which are often overlooked or marginalized (Arlinghaus and others, 2019). However, such management is hindered by data-collection gaps, poor capacity, incomplete governance and legislation, inconsistent objectives and regulations, regional differences in culture and governance, and competition over resources between commercial and recreational sectors, as well as access conflicts involving Indigenous communities.

Integrating information on marine recreational fisheries into stock assessments and management strategies is essential, yet operational objectives, data quality and performance metrics that go beyond simple management of yield and instead consider full recreational fisheries benefits are lacking. Co-management and adaptive approaches encourage collaboration among stakeholders, fostering conservation and sustainable resource use. Advanced digital tools and community science initiatives can enhance data collection and promote sustainable fishing practices. In addition, social equity issues, including gender and racial participation barriers, and environmental concerns such as lost gear, present challenges to the social licence of marine recreational fisheries.

To support sustainable marine recreational fisheries, new frameworks must address ecological, economic and social aspects, including improved regulatory compliance, cost recovery models, data integration and mechanisms to promote social development. Effective marine spatial planning, combined with fisher engagement in monitoring, can ensure the long-term viability of marine recreational fisheries and ecosystem sustainability by aligning management with biological, social and economic goals, so that marine recreational fisheries can be a flourishing component of sustainable ocean use into the future.

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Chapter 3
Energy

Introduction

The present chapter includes two subchapters, in which an integrated approach is taken to exploring the renewable and non-renewable resources of the world's oceans, including an examination of relevant economic activities, innovative approaches and social factors at the global and regional levels.

Subchapter 3A concerns offshore renewable energy (ORE), such as wind, wave and tidal energy. Their potential positive cumulative environmental effects are outlined, and it is highlighted that the proper handling of such resources could significantly reduce global carbon dioxide (CO_2) emissions (some 10% of the reductions required by 2050). Social equity is underlined as a priority to ensure that the expansion of ORE does not disproportionately affect already marginalized communities or perpetuate existing inequities.

Subchapter 3B concerns offshore and deepwater exploration of non-renewable oil and gas resources and begins with a description of the current magnitude and scope of these activities, which is followed by projections of future deepwater hydrocarbon exploration. The subchapter includes an analysis of the impacts, potential for disaster and longer-term effects of both hydrocarbon surveying activities and offshore installations. Lastly, the subchapter sets out the social perspective, highlighting that the offshore hydrocarbon industry's operations often intersect with the social and environmental concerns of local communities, leading to conflicts and challenges in securing public acceptance.

Emmett Sparling

Subchapter 3A
Offshore renewables

Key points

- Ocean-based renewable energy, such as offshore renewable energy (ORE), could deliver around 10% of the global CO_2 emission reductions required by 2050 to sustain a 1.5°C pathway, and ORE will be a vital tool in meeting the goal of tripling the world's installed renewable energy capacity, as set during the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change.
- ORE development has high potential for boosting employment and providing local economic benefits. Social equity should be prioritized to ensure that the expansion of ORE does not disproportionately affect already marginalized communities or perpetuate existing inequities.
- Effective policy strategies, such as technology push instruments (e.g. research and development grants), market pull instruments (e.g. feed-in tariffs and contracts for difference) and marine spatial planning, are necessary to advance the ORE sector and increase the roll-out of ORE technologies.
- Understanding the potential cumulative environmental effects of offshore renewables and implementing effective mitigation measures can reduce harm to marine environments and potentially lead to net positive gains for habitats and ecosystem processes.
- The development of offshore renewables can be part of the solution to the climate crisis if a sense of responsibility is maintained, best practices are followed in measuring potential environmental and socioeconomic effects by using standardized sustainability assessments, unacceptable changes are mitigated and plans are made to reverse course if irreparable damage is found to be being done.

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1. Introduction

Developing ORE globally will be pivotal to the energy transition and the decarbonization of the economy (Garavelli and others, 2024; UNFCCC, 2024). Not only can ORE play a role in mitigating global warming and reducing emissions by providing a clean and reliable source of energy, but it also provides opportunities for coastal economic revitalization through enhanced innovation, job creation and the provision of renewable energy to remote coastal locations, such as islands, for a just transition. It offers a clean growth pathway, transitioning the workforce and industries to meeting future development needs, while providing a sustainable means of meeting the growing energy demand.

Offshore wind energy will soon be generated on a large scale at sea, at which point it will be used to supplant conventional energy sources on national grids. Other more emerging marine energy technologies (wave energy, tidal current energy, ocean thermal energy conversion, salinity gradient energy and offshore floating solar) can complement the large-scale generation of electricity using offshore wind by filling gaps to ensure the secure, continuous and equitable provision of energy in off-grid applications. A key off-grid ORE application is electrifying islands and remote coastal communities, which currently generate electricity mainly from fossil fuels. Offshore renewables can provide stability and resiliency as wind and solar energy and energy storage are incorporated into sustainable microgrids (LiVecchi and others, 2019). Similarly, certain marine energy sources can generate power to be used at sea, replacing battery power on ocean observation and navigation platforms, replacing fossil fuels as aquaculture facilities move further offshore and eventually replacing coastal and transoceanic shipping fuels (LiVecchi and others, 2019). These emerging ORE solutions can be used to meet the growing need for electricity to power offshore data and computing centres, which are needed to support artificial intelligence.

The present subchapter provides an overview of ORE technologies, including their development status, opportunities, challenges and environmental and socioeconomic considerations, followed by an outline of an ideal pathway for ORE development up until 2050, wherein success will hinge on the ability to address the identified knowledge gaps.

2. Offshore renewable energy technologies that are emerging and available on the market

Development status

The present part of the subchapter contains an introduction to the different ORE technologies, including offshore wind energy, wave energy, tidal energy, offshore floating solar, salinity gradient energy and ocean thermal energy conversion, with a short description of each technology's working principles, resource potential and status. It is important to note that ORE technologies can also be referred to as marine renewable-energy technologies (as in the second *World Ocean Assessment* (Bebianno and others, 2021)) or ocean energy technologies (Ocean Energy Europe, 2024). According to a report commissioned by the High-level Panel for a Sustainable Ocean Economy, ORE could deliver around 10% of the global CO_2 emissions reductions required by 2050 to sustain a 1.5°C pathway (Hoegh-Guldberg and Northrop, 2023). Use of ORE depends on the efficiency, maturity and cost-effectiveness of the technologies. The working principles and stages of development of various ORE technologies are listed in table 1.

Table 1
Development status of various offshore renewable energy technologies

Offshore energy technology	Development status	Technology readiness level	Working principle
Offshore wind energy	Mature and in commercial operation	9	Wind turbines convert wind energy to kinetic energy via a rotating turbine, and then to electricity directly or via a drivetrain (i.e. the components that transfer the power from the moving blades to the generator) and a generator. Gravity base foundations are used for depths of up to 10 m, monopiles are economic for water depths of 20–40 m and jacket foundations are considered competitive for water depths of up to 70 m.
Floating offshore wind	Pre-commercial to early commercial phase	8	For deeper offshore areas, floating turbines are anchored to the seabed via mooring lines and have spar, semi-submersible or tension-leg platform designs (Jiang, 2021).
Wave energy	Demonstration phase to full-scale prototype phase (depending on technology type)	6–7	Wave energy converters are devices that convert energy from surface waves to electricity. There are three basic wave energy converter types (Falcao, 2010) which can be subclassified into: • Oscillating water column devices, which utilize the air pressure difference caused by the wave-induced water surface "up-down" movement • Overtopping devices, which collect the water that spills into a device as the waves pass and that water then passes through a turbine to generate energy • Oscillating bodies, which utilize the relative motions between a floating structure and a reference body to drive a generator and produce energy.
Tidal current energy	Demonstration phase (pilot projects in operational environment), then first farms, up to pre-commercial phase	7–8	Marine turbines are submerged devices that are used to extract energy from tidal currents. Tidal current turbines operate in seawater but have similarities to wind turbines in that they possess blades, drivetrains and support structures. Marine turbines require far smaller rotor diameters than wind turbines to achieve a similar power output, as seawater is much denser than air. Different configurations and prototypes of tidal turbine designs have been developed and megawatt-size turbines have been tested at sea (Ocean Energy Systems, 2021). Flow speed is a key factor in assessment of the available energy (Khare and others, 2019).
Tidal range energy	Mature and in commercial operation	9	Marine turbines are submerged devices that are used to extract energy from tidal ranges (where turbines form part of the system with a tidal barrage or tidal lagoon).
Offshore floating solar energy	Demonstration phase	5–6	Solar energy is created by the power from the sun as electromagnetic radiation, or solar irradiance. The intensity of solar irradiance is variable and depends on latitude, season, time of day, weather conditions, solar cycle, etc. In the ocean, solar energy could be extracted using solar panels (photovoltaic systems) fitted to dedicated floating platforms or to existing offshore structures.

Table 1 (*continued*)

Offshore energy technology	Development status	Technology readiness level	Working principle
Salinity gradient energy	Demonstration phase	5–6	Salinity gradient energy, also called blue energy, can be produced from the salinity difference between seawater and fresh water. This energy is typically generated using either: • pressure-retarded osmosis, where salt water and fresh water are separated by a membrane and mixed via osmosis, with the energy of the physical flow being extracted • reverse electrodialysis, whereby salt ions are transported through membranes to generate a charge (Han and others, 2021) • Ionic Nano Osmotic Diffusion technology, which is an evolution of reverse electrodialysis technology based on nanotechnologies.
Ocean thermal energy conversion	Demonstration phase (early demonstration phase for offshore ocean thermal energy conversion; onshore, the technology is already at technology readiness levels 7–8)	4–7	Ocean thermal energy conversion uses the thermal gradient between deeper cold seawater and warmer surface water to generate electricity using a heat engine. Areas of largest temperature gradient between deep and surface water (above 20°C, which is the lower threshold for ocean thermal energy conversion applications) occur in a belt in the tropics, especially in the western part of the Pacific Ocean and in the Indian Ocean.

Source: Prepared by the writing team.

Note: Technology readiness level ranges from 1, which is an innovative idea, to 9, which is a solution ready for market.

Opportunities and challenges

Opportunities and challenges related to the development of ORE are set out in table 2. In the first instance, ORE is likely to need price support until supply chain investments are made and industry learning is consolidated (see part 3 below). Governments can play a valuable role in reducing market risks, thereby reducing financing costs and ensuring lower fuel bills for consumers. To encourage market readiness, Governments might consider appropriate policies, stakeholders, grid connections and financing (Sajith and others, 2024; Aswani and others, 2021), and some good examples of regulatory frameworks to address such bottlenecks already exist. However, some countries are still at an early planning stage, meaning that the supply chain and operational readiness to deploy are limited. Developing economies may face additional financing barriers, and some may have particular market structures that hinder the penetration of ORE into the energy mix (Aswani and others, 2021; Cevasco and others, 2021). In all markets, the concept of risk-sharing, usually between the Government and the private sector, is integral to market stimulation as bidding in auctions and tenders requires a project developer to carry a large amount of the financial uncertainty and risk (Niezrecki, 2024) given that project approval can be very lengthy.

Table 2

Opportunities and challenges of various offshore renewable energy technologies

ORE technology	Opportunities	Challenges
All ORE technologies	ORE technologies could deliver around 10% of the global CO_2 emissions reductions required by 2050 to sustain a 1.5°C pathway and will be a vital tool in meeting the goal of tripling global installed renewable-energy capacity, as set during the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change. Harnessing the power of the oceans enhances energy independence and security for coastal communities. ORE technologies cause less noise disturbance than onshore solutions and are located close to demand centres, as almost three quarters of the world's population live within 50 km of the coast.	Relatively high levelized cost of energy, initial capital outlay, credit accessibility and insurance, inadequate support mechanisms and power pricing schemes. Port and harbours require investment to facilitate growth. A stable supply chain of critical materials used for renewable-energy devices is lacking and the process of developing new sources is lengthy. Extreme weather events, limited availability of suitable points of interconnection, lack of servicing and maintenance capabilities, lack of experience in cable installations. Ocean-use conflict, insufficient marine spatial planning, lack of public awareness, social acceptance and reliable metocean data. Differing viewpoints on the impact of ORE technologies on marine ecosystems and the visual effects on coastal landscapes.
Fixed offshore wind	High capacity factors offshore and generally very large project size (GW scale). Proven technology with significant cost reduction achieved in mature markets. Generation of economic growth through the creation of green jobs, which can be sustained over the 25-year lifetime of a project. The supply chain stimulates the economies of coastal communities, giving rise to new opportunities for local development, investments, knowledge transfer and capacity-building (Commercial, 2023; Oersted report, 2024) (see also part 3).	Limited to shallow-water depths. Port and harbours require investment to facilitate growth. Decommissioning and recycling of materials.

Table 2 (*continued*)

ORE technology	Opportunities	Challenges
Floating offshore wind	Higher capacity factor compared to fixed-bottom wind and other renewables. 80% of global potential is in deeper water (IRENA, 2024; Associates, 2023). The environmental impacts of floating offshore wind are lower than fixed-bottom offshore wind, particularly during installation, decommissioning and operation. According to the International Union for Conservation of Nature (IUCN), floating wind results in less seabed disturbance and generates less underwater noise. Floating wind may result in fewer conflicts with ocean users as it is located so far from the coast. However, continuous data collection and assessment are needed to further support these statements (Kausche and others, 2018; Associates, 2023). The technology is delivering power to grids, with multiple floating wind farms already in service, including in China, Portugal and Scotland. The United States and other countries have conducted auctions specifically for floating offshore wind energy. Notably, the Bureau of Ocean Energy Management held an offshore wind lease sale in the Pacific region, focusing on areas off the coast of California.	Need for enabling regulatory frameworks for floating offshore wind development. Innovation in foundations, moorings and grid infrastructure ongoing, with several component concepts being explored (no convergence achieved yet) (Associates, 2023). Investment needed to achieve greater project scales. Technological consolidation required for increased standardization and certification and to facilitate stable growth (Kausche and others, 2018; Associates, 2023). While progress is evident, further cost reductions and scaling up are still needed to achieve full commercial maturity.
Wave energy	Immense potential and promise, predictable source of energy (Barua and Salauddin Rasel, 2024). The theoretical potential annual global wave energy production is estimated to be 29,500 TWh (Ocean Energy Europe, 2024; Barua and Salauddin Rasel, 2024). Global cumulative installed wave energy potential is 23.3 MW (51% of which is in Europe) (Ocean Energy Europe, 2024).	Technology for grid integration, mass production and commercialization not yet matured (Earth.org, 2023; Barua and Salauddin Rasel, 2024). High costs of installation and ongoing maintenance. Impact on marine life not fully understood (Earth.org, 2023).
Tidal current energy	The estimated global tidal energy available for extraction per year ranges between 150 and 800 TWh, with theoretical potential estimates up to 1,200 TWh (IRENA, 2024). The global cumulative installed tidal current energy potential (i.e. the total capacity of all tidal current devices that have been installed, even if some of them have now been removed, operating at their maximum in ideal conditions) is 36.3 MW (nearly 77% of which is in Europe) (Ocean Energy Europe, 2024). Significant growth in recent years (Ocean Energy Europe, 2024). Highly predictable resource. Advancements in technology are improving efficiency and cost-effectiveness. Growing evidence of low environmental impact (Ocean Energy Europe, 2024).	High initial costs and infrastructure requirements. Concentration of resource in specific regions, limiting widespread implementation (Green.org, 2024; O'Doherty and others, 2018; Onoufriou and others, 2021). Continuing permitting challenges due to uncertainty of effects.

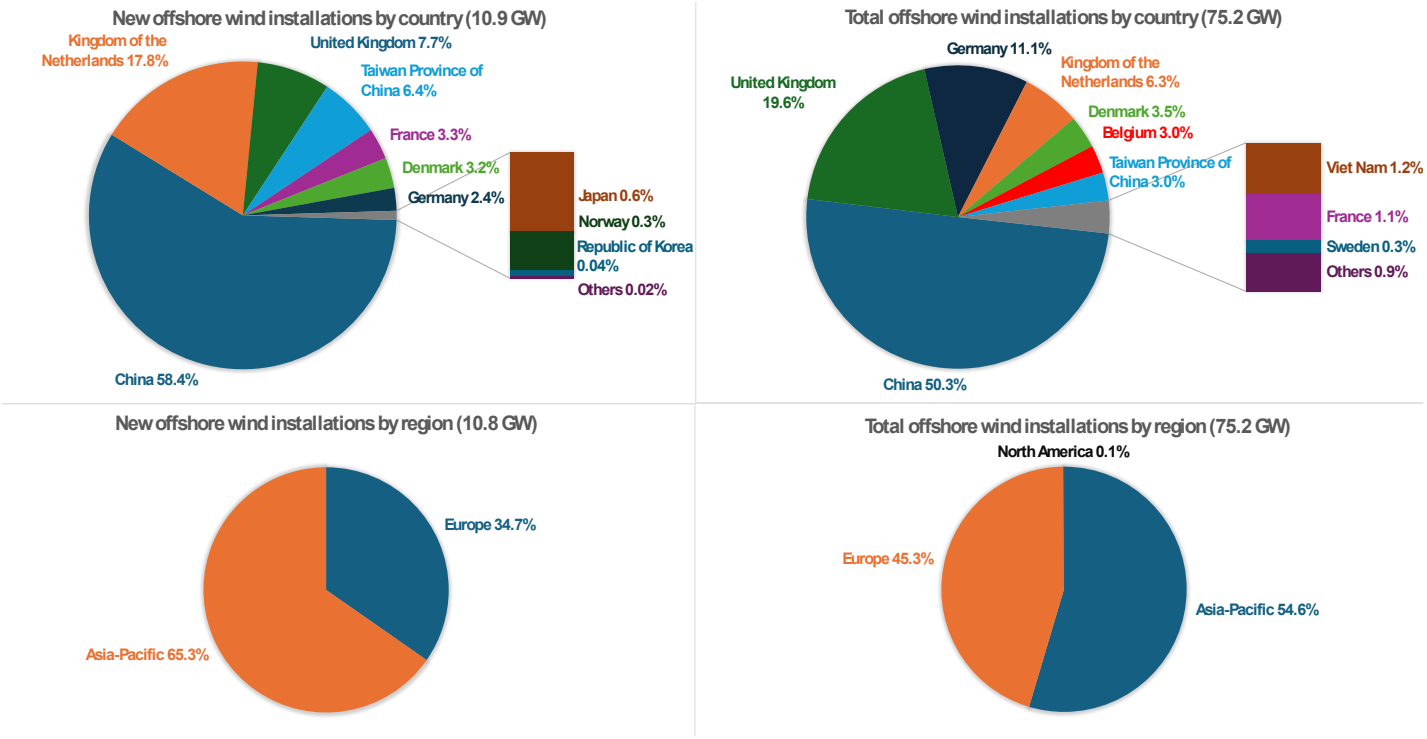
ORE technology	Opportunities	Challenges
Tidal range energy	Highly predictable resource. Established technology.	High-cost infrastructure. Significant impact on marine ecosystems.
Offshore floating solar energy	Significant resource potential. The sector has been rapidly developing over the past five years in Europe (particularly in Belgium, France and the Kingdom of the Netherlands), as well as in China and Singapore, where two pilot deployments have shown survivability through major storms. Multi-source offshore energy parks or co-use of offshore space by combination ORE technologies, such as offshore wind with offshore floating solar or wave energy, have been promising developments in diversification in (and complementarity of) electricity sources, which will help to overcome the inherent intermittence of renewable-energy sources, including ORE sources.	In seas with relatively high waves, survivability can be an issue due to the large forces exerted by waves, meaning higher strength floating platforms are needed (Vo and others, 2021). Survivability and maintenance can be issues in offshore locations due to wave action and distance to shore, although automated maintenance is under development.
Salinity gradient energy	Salinity gradient energy is highly available and predictable; plants can be located either at naturally occurring gradient sites, such as where rivers flow into the sea, or alongside other infrastructure, such as desalination plants (Cipollina, 2016). Blue energy can be produced without any operational CO_2 emissions. Environmental impact can be minimized as neither water nor salt is consumed in the process and the installations can be located underground or in low-rise buildings. No significant noise pollution (Kempener and Neumann, 2014). The worldwide theoretical potential for salinity gradient power has been estimated at 1,650 TWh/year (Skråmestø and others, 2009).	Technological challenges to scaling up include quality of the membranes; biofouling; development of the membrane modules; pre-treatment of water; production of durable and affordable membranes at scale. Operation and maintenance costs are high.
Ocean thermal energy conversion	Continuously available, significant resource potential and a very high capacity to produce energy (Ocean Energy Systems, 2021; Herrera and others, 2021). Can be utilized for baseload power generation, refrigeration, seawater desalination and deepwater aquaculture, greatly improving economic benefits.	Low energy conversion efficiency (Chen and Huo, 2023). Need to improve thermal efficiency using solar energy or industrial heat. High project capital costs exacerbated by relatively low power outputs (IRENA, 2014; Ocean Energy Systems, 2021).

Source: Prepared by the writing team.

Prospective development, including regional potential

Global installed capacity of offshore wind was 75.2 GW in 2023, (Global Wind Energy Council, 2024) which is more than double what it was at the time of writing of the second *World Ocean Assessment* (Bebianno and others, 2021). The International Renewable Energy Agency (IRENA) and International Energy Agency project that at least 380 GW offshore wind will be needed by 2030, and over 2,000 GW by 2050, to keep the world on track for 1.5°C. In 2023, 11 GW offshore wind was connected to the grid, which is a 24% year-on-year increase, the second highest yet (see figure I).

Figure I
New and total offshore wind installations worldwide in 2024



Source: Global Wind Energy Council, *Global Offshore Wind Report 2024*.

Membership of the Global Offshore Wind Alliance, a diplomatic, multi-stakeholder initiative founded by the Global Wind and Energy Council, IRENA and the Government of Denmark, has grown to include over 20 Governments. These Governments have pledged to collaborate on installing 380 GW offshore wind by 2030 and 2,000 GW by 2050 (Global Offshore Wind Alliance, 2024).

There is still an implementation gap between declared targets and the rate of annual installations. Permitting, finance, supply chain and grids are areas that remain key enablers to achieve growth targets and to propel offshore wind power development into a new phase of even faster growth. The World Bank Group found that blended and concessional finance would be important in enabling emerging markets and developing economies to gain access to financing for offshore wind. A report published in 2024 in the United Kingdom of Great Britain and Northern Ireland found that the offshore wind workforce needs to grow sixfold, offshore wind capacity needs to increase sevenfold and current capacity and project build-out rates need to be four times faster if the goals set are to be reached by 2050 (Supergen ORE Hub, 2024).

The planned uptake of tidal stream energy in Europe has increased since 2023, with the United Kingdom and France contracting 70 MW of tidal stream capacity through revenue support systems. This is expected to lead to a global capacity of well beyond 127 MW by 2030 (Ocean Energy Europe, 2024).

A total of 13.3 MW of wave energy has been installed in Europe since 2010, of which 1 MW is currently deployed. The other installations have been decommissioned following the completion of testing and demonstration programmes (Ocean Energy Europe, 2024). The rate of deployment of wave energy devices had slowed but is growing again towards levels recorded before the coronavirus disease (COVID-19) pandemic. Beyond Europe, the United States of America and China have announced development targets and voiced support for ORE (Ocean Energy Europe, 2024).

Project development, including supply chain and grid connection challenges

To unlock the full potential of ORE and achieve ambitious targets, a robust supply chain for installation components, installation and maintenance vessels, and the development of harbours for installation purposes are critical. In Europe, America and Asia, several countries have set ambitious targets – some by 2030 – for offshore developments, necessitating rapid harbour development and an increase in the qualified workforce. In Oceania, the Government of Australia has identified six regions for offshore wind development, which will require new or expanded onshore ports and grid infrastructure to support the industry.

Current renewable-energy production and decarbonization targets are driving a rapid expansion of offshore renewables worldwide, which will help to mitigate climate change. Many of the ORE components require "critical materials",[1] including cobalt, copper, graphite, iridium, lithium, manganese, nickel, platinum and selected rare earth elements. Since sources of these materials are often very localized, their supply involves structural vulnerability to supply chain disruptions. Various attempts at the diversification of sources of critical materials have been proposed, such as the Critical Raw Materials Act by the European Commission (European Commission, 2024). Special attention is needed for the supply of copper as demand is rising across multiple sectors, including ORE, other renewable-energy technologies, and specific types of car batteries. Copper could soon become a major bottleneck, due not only to limited geological availability, but also to rapid acceleration in demand.

Deep-sea mining could become an option for more equitable access to critical materials, but does carry a set of potential uncertainties and environmental risks, including disruptions to ocean carbon sequestration processes, which could amplify climate change (Toro and others, 2020). A more sustainable and strategic approach is "urban mining", which is using recycled copper from electronic waste. Urban mines potential is nearly equivalent to land-based reserves. Given that copper is highly recyclable, fostering circular economy strategies is essential.

Another method of critical materials extraction that is currently in an advanced stage of research and development is from seawater containing critical minerals at low concentrations. Extraction requires the use of large volumes of seawater; the process is being examined in conjunction with emerging ORE technologies such as ocean thermal energy conversion (Sharkh and others, 2022). The environmental impact of this new method is to be determined but can likely cause less impact compared to deep-sea mining.

The lack of a stable supply chain for critical materials used for renewable-energy devices and the lengthy process of developing new sources (e.g. exploration and mining infrastructure development) may result in critical materials becoming another bottleneck in ORE large-scale roll-out. On the positive side, the situation may increase research and development in circular strategies for raw materials used in renewables.

Comprehensive project sustainability assessments are vital for fostering resilient ORE investments and ensuring sustainable energy development. Such assessments should include the risks posed by projects to the sustainability of marine ecosystems. Assessments should consider both positive impacts (handprints) and negative impacts (footprints), as well as impacts on ecosystem services, such as cycle assessments of components used and other aspects of sustainability (De Luca Pena and others, 2024). Key risks (i.e. technology-related, deployment-related, regulatory, financial and reputational) can be effectively managed to protect the environment. These risks and their potential impacts are summarized in table 3.

[1] See www.irena.org/Publications/2023/Jul/Geopolitics-of-the-Energy-Transition-Critical-Materials?.

Table 3
Risks associated with the deployment of offshore energy installations

Risk dimension	Definition	Cause of risk	Mitigation	Environmental impact	References
Technology risk	Risk of failure or underperformance of ORE technologies	Equipment manufacturers Technology developers Research institutions	Insurance Proven technology Comprehensive technology evaluations	Hazardous material spills	Gatzert and Kosub (2016) Zhou and Yang (2020) Vanegas-Cantarero and others (2022)
Deployment/ survival	Risk of challenges in the installation and maintenance of ORE infrastructure	Contractors Environmental conditions	Project risk assessments Experienced contractors Regular maintenance	Disruption to marine habitats and biodiversity Debris that harms marine life	Chou and others (2021)
Regulatory	Risk from changes in laws or regulations affecting ORE projects	Legislators Regulatory agencies Changes in government policy	Engage with policymakers Monitor regulations Ensure compliance		Gatzert and Kosub (2016) Zhou and Yang (2020)
Financial	Risk arising from scarcity of capital or insufficient income-generating streams	Traditional financial institutions Investors Market behaviour	Diverse funding sources (e.g. crowdfunding or peer-to-peer lending) Strong investor relations	Compromised environmental protections during construction and operation	Gatzert and Kosub (2016) Steffen (2020) Zhou and Yang (2020)
Reputational	Risk of damage to a company's image due to environmental or operational issues	Media Environmental organizations Public perception	Transparent communication Public engagement Strong environmental, social and governance practices	Decreased support for renewable-energy initiatives Heightened scrutiny impeding project development	Zhou and Yang (2020)

Source: Prepared by the writing team.

3. Socioeconomic aspects

The increased uptake of ORE is expected to lead to change in some coastal communities, which will bring about social and economic impacts (Glasson and others, 2020). The socioeconomic impacts of global ORE development should be evaluated alongside other offshore energy sectors, such as oil and gas, which may have partly comparable impacts (United Nations Environment Programme Finance Initiative, 2022). The social impacts of ORE have not been comprehensively considered and there is a need for further research in this space (European Court of Auditors, 2023). As outlined in table 4, the consideration of socioeconomic impacts requires clarification on distribution, geographical and temporal scope and the nature of the impact (Glasson and others, 2020).

Table 4
Complexities of identifying the socioeconomic impacts of the development of offshore renewable energy infrastructure

Socioeconomic impact criterion	Examples
Distribution Understanding the ways in which the harms and benefits are distributed. Are specific groups more marginalized than others? Do specific groups benefit more than others? Are there issues of equity or environmental justice? The term "environmental justice" in the present *World Ocean Assessment* refers to mechanisms for ensuring justice and compliance with human rights obligations in relation to environmental issues.	The development of large-scale ORE infrastructure may affect already marginalized communities, both positively and negatively (Bourg-Meyer, 2022). In fact, the most marginalized communities are often those most negatively affected during the development of ORE. Mechanisms may be used to ensure that there is an appropriate distribution of the harms and benefits, such as community benefit schemes, compensation for loss of livelihood and provisions to support women and minority-owned businesses in the supply chain (Bourg-Meyer, 2022). Ensuring equitable distribution of impacts begins in the energy planning process, including siting, and involves early, frequent and appropriate community engagement. Equitable processes include appropriate engagement and decision-making, such as giving communities a voice in decision-making processes. Such processes are most successful when appropriate mechanisms for transparency and accountability are included.
Spatial scale How to define the community by which to measure the impacts of ORE infrastructure?	There are many components that comprise ORE infrastructure and this spatial scope is important as the social impacts may be broad in geographical scope when the whole supply chain is considered. Furthermore, there is no clear delineation of what constitutes a community in relation to offshore infrastructure as there would be for infrastructure on land. The infrastructure is offshore, but the people who are affected live onshore and potentially comprise a range of different groups that are based in different locations and are affected in different ways.
Temporal scope Over what time period should the impacts be considered?	There are several phases in the life cycle of ORE infrastructure, with different activities taking place in each one. These activities will generate different impacts and there may also be impacts associated with transitions between phases. Understanding the cumulative impacts of ORE developments on coastal communities is therefore significant. Research suggests that there is a need for more long-term longitudinal studies on the socioeconomic impacts of ORE (Bingaman and others, 2022).
Nature	The nature of the impact can be tangible, intangible, direct or indirect. Impacts can also be negative (e.g. loss of income or damage to visual amenity) or positive (e.g. reduction in air pollution leading to increased health outcomes, or an equitable community benefits scheme). Specific sectors or groups of people may be more affected than others. Existing ocean users such as fishers are a good example of this. In terms of fisheries, there are social impacts due to the displacement of fishing activities to enable ORE developments. The displacement of fishing activities can lead to further impacts and displacements within the community, which are likely to be different from place to place. These impacts are not only felt in economic terms but also in social terms through loss of tradition and social fabric.

Source: Prepared by the writing team.

Social considerations in the continued development of offshore renewables

As outlined in table 5, identifying the social impacts of ORE is complex. However, the need to embed equity in the development of ORE and energy transitions more broadly is the crux of all social considerations. It is imperative that the increased uptake of ORE do not reinforce the status quo or exacerbate wealth inequality and existing inequities. Equity therefore needs to be foregrounded in the processes and outcomes of ORE development, which will subsequently help to advance some sustainability goals (Villavicencio Calzadilla and Mauger, 2017). While the development of ORE has been linked to the advancement of the Sustainable Development Goals, the relationship between these two phenomena is often complex and the development of ORE-related infrastructure can both enable and inhibit the advancement of the Goals (Tian and

others, 2024). Processes such as planning, procurement and investment are significant in ensuring the sustainable development of the ORE industry (Bourg-Meyer, 2022).

The social aspect of ORE could involve creating jobs for members of underrepresented groups, including women, ethnic minorities, Indigenous Peoples, sexual minorities, persons with reduced mobility and young persons. Although the energy transition is under way in many countries, there is still a gap in job creation for underrepresented groups, according to the International Labour Organization (ILO). Furthermore, initiatives such as the Offshore Wind Sector Deal, published in the United Kingdom in 2019, can play a crucial role in fostering inclusive representation in the ORE sector. The deal was an industry commitment that set targets to increase diversity by raising the representation of women in the offshore wind workforce from 16% in 2018 to at least 33% – with an ambition to reach 40% – by 2030.

Beyond voluntary commitments, legal frameworks in several countries also support inclusivity in offshore wind development. In the United States, impact assessments for offshore wind projects under the National Environmental Policy Act evaluate the social impacts of offshore wind projects. Similarly, in Canada, the Impact Assessment Act requires assessments of ORE projects to consider gender minorities and other underrepresented groups, promoting fair participation in the sector. In the United Kingdom, the Equality Act (2010) provides a legal foundation for advancing diversity and inclusion across industries, reinforcing efforts like the Offshore Wind Sector Deal.

In order to put the rights of Indigenous Peoples at the forefront of energy transitions, including in the development of ORE, the principles of free, prior and informed consent, as set forth in the United Nations Declaration on the Rights of Indigenous Peoples, should be upheld (Organisation for Economic Co-operation and Development (OECD), 2024; United Nations, 2007). Furthermore, mechanisms should be enabled to support Indigenous, traditional owner and local community knowledge and Indigenous-led research and governance and to enhance the importance of Indigenous knowledge systems (Doyon and others, 2021). At the same time, increasing Indigenous representation requires recognizing the systemic barriers to participation and leadership for Indigenous Peoples (Doyon and others, 2021).

Decisions relating to the use of ocean space should acknowledge the plurality of human relationships with the ocean (Allison and others, 2023). Social acceptance can influence the success of the development of ORE projects (European Court of Auditors, 2023). Research shows that often there is a disconnect between the broad support for the development of offshore renewables among the general public and local resistance in adjacent communities (Devine-Wright and Howes, 2010). Place-based understanding and approaches will therefore be essential in the continued development of ORE.

Conflict arising in relation to the use of marine space, including spatial exclusion of fishers, can be mitigated by marine spatial planning (European MSP Platform, 2019). Conflict should not be seen as necessarily negative, as it is often through conflict that better social and environmental outcomes can be achieved. However, it is important that appropriate mechanisms for navigating this conflict be developed (Knol-Kauffman and others, 2023; Tafon and others, 2021; Saunders and others, 2024).

Economic considerations

ORE development, including wind power, tidal power, wave power and other technologies, creates demand for a wide range of components and services, leading to new jobs and local economic development. ORE development therefore holds significant potential for job creation, provided that training programmes expand and workforce initiatives adapt to evolving demands. The High-level Panel for a Sustainable Ocean Economy found that offshore wind has a higher capacity for jobs than the fossil fuel industry and in general has a better gender balance (Lubchenco and Haugan, 2023). IRENA estimated that a 500-MW offshore wind project directly creates 2.1 million person-days of work, or about 10,000 person-years of work, over its lifetime. Offshore wind presents an opportunity to revitalize coastal towns, cities and communities, where new investments can regenerate areas that have previously seen economic decline.

The projections of potential employment from ORE for certain countries and regions are shown in table 5. However, significant challenges remain in ensuring job supply for the growth of the ORE sector. As the sector expands, the demand for skilled workers will increase, especially with the ambitious development goals set by multiple nations. Job creation is constrained by factors that include the number of large-scale projects, regulatory complexities, technological advancements, and financing and investments, as well as training and skills development. The ORE sector requires a specialized workforce (Sdoukopoulos and others, 2019; Stefek and others, 2022) but, in many regions, there are not enough

training programmes to meet the sector's needs, leading to skills gaps in areas such as advanced engineering and operational expertise (Sdoukopoulos and others, 2019; López-Morado and others, 2024). The high costs of training, alongside rapidly evolving technologies, complicate efforts to equip the workforce (Stefek and others, 2022). Investing in robust training frameworks and education initiatives is essential to meet growing employment demands and ensure the long-term sustainability of the sector (Arbic and others, 2024).

Socioeconomic impact assessments

Socioeconomic impacts are assessed as part of the environmental impact assessment process when developers are applying for a licence or consent. The intention is to identify the potential impacts and to explore mitigation and enhancement measures.[2] However, impact assessments may not adequately show the risks and opportunities (Scotland's Marine Assessment, 2020) nor accurately reflect social and cultural values that are not readily transferable as quantifiable metrics. Both qualitative and quantitative methods will be needed to accurately measure the full scope of socioeconomic impacts (Glasson and others, 2020).

Table 5
Projected job creation potential of the offshore wind energy sector

No.	Region/country	Time frame	Capacity	Jobs created
1	United Kingdom	2030	43–50 GW	100 000[a]
2	United States	2030	30 GW	15 000–58 000
3	European Union	2030	70 GW	77 000
4	China	2025	140 GW	–
5	Japan	2030	10 GW	35 000
6	Republic of Korea	2030	14 GW	770 000[a]

[a] According to industry-level projections.

Source: Prepared by the writing team.

4. Governance of offshore renewables

Strong governance mechanisms and supportive policies are essential to attract the necessary financial investment to support the expansion of ORE while also working towards social and environmental outcomes. Governance is a system of organization and operation that includes components such as decision-making, compliance and accountability. Supportive policies will enable the technology to reach commercial-scale implementation while ensuring that this expansion aligns with sustainable objectives. It is crucial to foster policies that promote long-term consistent deployment trajectories and an accelerated cost reduction rate. In the present part, various policy strategies that have been effectively used as governance mechanisms to encourage the advance of the sector are explored.

Policy based on both "technology push" and "market pull" instruments is effective for the development of OREs. Those instruments are essential for guiding technology through the various stages of the innovation chain, effectively supporting its development from the conceptual stage to initial adoption and widespread use. Some policy measures are aimed predominantly at advancing technologies in their early stages, while others play a crucial role in later stages, moving towards broad market acceptance.

The International Vision for Ocean Energy, outlined in the road map by the International Energy Agency Technology Collaboration Programme on Ocean Energy Systems, serves as a strong example of how the balance between push-and-pull policies is critical for advancing ocean energy technologies.[3]

"Technology push instruments" are designed to encourage the research and development of new technological ideas and advance them to the stages of demonstration and initial commercialization. Notable examples include tax credits for research and development, grants, prizes, concessional financing and matched equity funding. Such support is critical in the early stages of technology development and implementation as it makes innovative projects more attractive to private investors. Government funding for research and development is vital for technological innovation in this sector and should include funding for both basic and applied research, as well as support for demonstration projects to prove their

[2] See guidance published by the International Association for Impact Assessment at www.iaia.org.

[3] See www.ocean-energy-systems.org/publications/oes-documents/market-policy-/document/ocean-energy-and-net-zero-an-international-roadmap-to-develop-300gw-of-ocean-energy-by-2050/.

feasibility and performance under real sea conditions. It is important that such measures be focused on areas identified as priorities to enhance the performance of devices and reduce costs associated with development, implementation, maintenance and decommissioning. Such support mechanisms are particularly suited for promoting international collaboration, which is a key factor in accelerating cost reduction. Multilateral development banks, such as the World Bank and the Asian Development Bank, can play a significant role in promoting new technologies because they offer funding and risk mitigation that can attract additional private sector investment, which is particularly important for large-scale demonstration projects.

A strong illustration of technology push in action is seen in projects funded under the European Green Deal and Horizon Europe. These initiatives include multi-source offshore energy parks (European Scalable Offshore Renewable Energy Sources (EU-SCORES), 2024), tidal array energy parks[4] and wave energy parks supported by the European Union Innovation Fund (Saoirse wave energy project, 2024; Seaworthy project, 2024). The EuropeWave programme, supported by the Basque Country and Scotland along with the European Commission, represents another example of coordinated efforts to drive innovation in ocean energy technologies.

"Market pull" instruments are essential for developing a commercial marine energy sector. The two most relevant financial instruments used to encourage the development of marine renewable energies have been feed-in tariffs and contracts for difference, which have each been implemented in various countries. Feed-in tariffs offer long-term contracts to energy producers, guaranteeing them a fixed price for the electricity generated, which helps to mitigate the financial risk associated with the high initial costs of marine renewable-energy projects. Similarly, contracts for difference stabilize revenues for energy producers by ensuring that they receive a fixed price for the energy produced, regardless of market fluctuations. An illustrative case is the United Kingdom, where contracts for difference are the Government's main mechanism for supporting low-carbon electricity generation.[5] There have been six auctions, or allocation rounds, to date, which have seen a range of different renewable technologies competing against each other for a contract. They have been successfully implemented to boost the offshore wind energy sector and, more recently, the tidal energy sector.

In the United States, east coast offshore wind projects have been experiencing financial stress. Macroeconomic factors, such as rising costs of materials, supply chain disruptions and increases in the cost of capital due to increased interest rates, have, in combination with regulatory issues, brought about these challenges. Many contracts were agreed prior to the COVID-19 pandemic and certain geopolitical events, and did not include sufficient indexation linkages. Furthermore, issues such as slow permitting and differing supply chain requirements at the state level have increased risk and cost of capital. This experience highlights the need for better financial support mechanisms and risk mitigation strategies, such as indexation of offtake contracts, but also the need for clear governance and regulation that harmonizes requirements between state and federal regimes and recognizes the importance of efficient permitting procedures.

Another crucial aspect of governance for the development of marine renewable energy is the setting of clear and ambitious targets, accompanied by a clear and specific plan to deliver on those targets, with yearly milestones. Such targets demonstrate the Government's commitment to encourage investment and foster technological innovation in renewable energy (examples of offshore wind in Europe are set out in table 6). This is particularly important in the ORE sector, where the long-term financial viability of projects is critical for investors. In addition, these targets allow policymakers to align regulations, subsidies and support mechanisms with a common objective. Most importantly, targets and associated road maps and plans give confidence to investors and manufacturers to invest in facilities and projects. Targets act as catalysts for an energy transformation. For example, the European Union has set a target of 300 GW of offshore wind capacity by 2050, a significant increase from the approximate 12 GW in recent years. This ambitious goal is part of a broader strategy to achieve carbon neutrality and strengthen the energy independence of the bloc. The Kingdom of the Netherlands has set an ambitious target of achieving 3 GW of offshore floating solar capacity by 2030, showcasing its commitment to diversifying and expanding its renewable-energy portfolio.

4 See www.euro-tides.eu and www.offshore-energy.biz/nova-innovation-secures-e20m-from-eu-for-4mw-tidal-energy-project.
5 See www.cfdallocationround.uk/about.

Table 6
Offshore wind energy capacity targets (GW)

	Year					
	2027	2030	2035	2040	2045	2050
European Union		111				317
United Kingdom						
Kingdom of the Netherlands		43–50[a]				
Germany		22.2		50		70
Denmark		30	40		>70	
Belgium		12.9				
France		5.7		8		
Poland			18			45
Norway		10.9[b]				
Ireland				30		
Spain		7		20		37
Portugal		3				
Greece		2				
		2				

[a] Including 5 GW floating offshore wind.
[b] In operation or under development by 2027 (Global Wind Energy Council, 2024).

Source: Prepared by the writing team.

A well-designed regulatory framework is especially essential for the development of emerging offshore renewables. As the sector progresses globally, concerns about the potential effects of such devices on marine animals, habitats and the broader environment remain a significant challenge. To address those concerns effectively, a regulatory framework that provides clarity and predictability for developers is needed. Such a framework would outline the requirements and procedures necessary for the implementation of projects at sea to ensure that projects are both feasible and sustainable. To encourage growth in the sector, it is important that regulatory frameworks include effective licensing processes that minimize bureaucratic barriers, thereby speeding up the deployment of new technologies and ensuring that project timelines are manageable, while not compromising on social and environmental standards. Equally important is the need for efficient environmental impact assessments. As understanding of the potential environmental effects of ORE projects grows, environmental impact assessments should be streamlined to focus on assessing risks that are significant and warrant careful study. In addition, the regulatory framework should incorporate mechanisms to retire environmental risks (i.e. recognizing and managing risks once sufficient data are gathered), thereby enabling the industry to move forward confidently while maintaining high environmental standards. Notably, adaptive management strategies, which allow for adjustments based on real-time environmental monitoring, have been promoted in various countries.

Another important aspect of governance is marine spatial planning, which allows for the strategic allocation of marine spaces and ensures that OREs can coexist with other maritime activities, such as navigation, fishing and tourism. Marine spatial planning helps to manage the spatial and temporal distribution of human activities in marine environments, optimizing resource use while minimizing conflicts and environmental impacts. An innovative application of marine spatial planning is the adoption of multi-use strategies, which involve the co-location of different activities in the same marine area. By gathering data and knowledge for the planning area and engaging with affected stakeholders, marine spatial planning processes can support co-location of different activities in the same area.

As an example, China is now conducting 3-dimensional development of ocean space to encourage more efficient and intensive utilization of marine resources. This approach involves the division of marine areas into vertical layers (e.g. the surface, water body, seabed and subsoil) to determine the use of the marine area on the basis of actual conditions, as well as co-location of offshore floating solar photovoltaics and aquaculture, offshore wind farms and marine ranching, and offshore wind farms and tourism. The European Union's maritime spatial planning directive exemplifies how marine spatial planning can be effectively implemented: the directive requires European Union member States to develop maritime spatial plans that balance economic, social and environmental objectives, including the integration of ORE with other marine uses, thereby supporting the European Union's goals for sustainable growth of maritime economies and the responsible use of marine resources. The directive emphasizes a collaborative approach, involving stakeholders at all levels in the planning process to ensure that the plans reflect a broad range of interests and insights. Similarly, the "area passports" concept in the Kingdom of the Netherlands represents an innovative approach to enabling the coexistence of multiple offshore activities, such as energy production, aquaculture and other uses of the North Sea. Area passports help stakeholders to understand which activities can be integrated into a particular area, promoting multi-use strategies that optimize the use of marine resources while minimizing conflicts.

5. Environmental impacts

Understanding the risks that ORE production pose to marine animals, habitats and ecosystem processes requires specificity that links each part of an offshore device or system to species, habitats and processes. Using a stressor-receptor framework allows the attributes of each stressor (portion of device or operation that can cause stress, injury or death) to be linked to the specific receptor (animals, populations, habitats, oceanographic and ecosystem processes) of concern (Hasselman and others, 2023). The key stressors and receptors of concern for offshore renewable technologies are listed in table 2. Eight major stressors have been recognized by the marine energy and offshore wind communities (Garavelli and others, 2024; Maxwell and others, 2022):

- Collision risk: animals colliding with moving turbine blades (under water for tidal and ocean current turbines, in the air for wind turbines)
- Underwater noise: natural sounds under water being masked by noise from marine energy and offshore wind energy
- Electromagnetic fields: emissions from power export cables and underwater substations
- Changes in habitats on the seafloor and in the water column
- Changes in oceanographic conditions due to the presence and operation of devices
- Entanglement with multiple mooring lines securing systems
- Displacement: presence of many devices affecting animal migration and movements
- Chemical releases: on-board chemicals (for offshore wind, ocean thermal energy conversion and salinity gradient energy) released into the ocean.

Levels of confidence for some of the stressor-receptor interactions are still being established, while the results for some technologies, such as offshore floating solar, are inconclusive and require further research. However, the general environmental risks and impacts related to the deployment of infrastructure offshore are similar to those related to offshore non-renewables described in subchapter 3B.



Renee Capozzola

Table 7

Offshore technology stressors, receptors and potential mitigation strategies

Stressor	Offshore technology	Receptors	Potential effects	Mitigation	Citations
Collision risk	Wave	Seabirds	Considerable underwater structures, especially any moving parts, present an enhanced risk of collision or entrapment.	Depends on the technology employed, but risk is generally low as seabirds spend limited time under water.	Greaves and others (2016)
	Tidal, ocean current	Marine mammals, fish, sea turtles, diving seabirds	Injury, death.	Monitor for collision; potential for turbine shutdown.	Garavelli and others (2024)
	Ocean thermal energy conversion	n/a			
	Salinity gradients	n/a			
	Fixed offshore wind	Birds and bats (when present)	Injury, death.	Monitor for collision by using radar technology and thermal and optical cameras to detect animal movement; potential for turbine shutdown. Deploy early warning systems such as adjusting turbine operation, warning or deterring birds, reducing the number of lights or lowering light intensity, and using vision-based mitigation (e.g. monochromatic painting of a blade to increase visibility).	Martin and Banks (2023) Croll and others (2022) Ladeke (2017) May and others (2020)
	Floating offshore wind	Birds and bats (when present)	Injury, death.	Monitor for collision by using radar technology, thermal and optical cameras to detect animal movement; potential for turbine shutdown. Early warning systems such as adjusting turbine operation, warning or deterring birds, reducing the number of lights or lowering light intensity, monochromatic painting of a blade to increase visibility.	Schneider and others (2024) Croll and others (2022)
	Offshore floating solar photovoltaics	n/a			

Table 7 (*continued*)

Stressor	Offshore technology	Receptors	Potential effects	Mitigation	Citations
Underwater noise	Wave	Marine mammals, some species of fish	Installation noise can cause physical harm and/or cause animals to leave an area temporarily or permanently; operational noise can mask critical navigation and communication functions.	Monitor for underwater noise to ensure that it does not exceed regulatory or safe levels.	Garavelli and others (2024)
	Tidal, ocean current				
	Ocean thermal energy conversion				Copping (2023)
	Salinity gradients	n/a			
	Fixed offshore wind	Marine mammals, some species of fish	Installation noise can cause physical harm and/or cause animals to leave an area temporarily or permanently; operational noise can mask critical navigation and communication functions.	Schedule activities to avoid sensitive periods, deploy noise mitigation strategies (e.g. bubble barrier) and use innovative low-noise piledriving techniques. Establish noise-free zones or buffer zones around sensitive species' habitats.	Bennun and others (2021) Ioannou and others (2019) Msigwa and others (2022) Stoeber and Thomsen (2021) Brandt and others (2018) Agardy and others (2007)
	Floating offshore wind				Rezaei and others (2023)
	Offshore floating solar photovoltaics	n/a			

Stressor	Offshore technology	Receptors	Potential effects	Mitigation	Citations
Electromagnetic fields	Wave	Electro- and magneto-sensitive species: some elasmobranchs (e.g. sharks, rays and skates), some bony fish, and some crustaceans (e.g. crab and lobster)	Small amounts of electricity from marine energy electromagnetic field signals are below harmful levels.	Use shielded cables and bury cables to protect animals from signals.	Garavelli and others (2024) Ayyildiz and Erdogan (2024)
	Tidal, ocean current				
	Ocean thermal energy conversion		Offshore floating ocean thermal energy conversion cables could emit sufficient electromagnetic fields to potentially cause harm.		Copping (2023)
	Salinity gradients		...		
	Fixed offshore wind		Offshore wind cables transmit enough power to potentially cause harm.	Bury cables to protect animals from signals.	Taormina and others (2018)
	Floating offshore wind				Schneider and others (2023) Hermans and others (2024) Benjamins and others (2024)
	Offshore floating solar photovoltaics		Unknown, but full-scale installations likely the same as offshore wind.		
Habitat changes	Wave	Anchors, foundations and cables on the seafloor; mooring lines and floats/ platforms in the water column	Where cables are buried, benthic habitats can be disrupted and can take weeks or months to recover. Loss of soft bottom habitats creates new hard-bottom habitats (can be beneficial for some organisms). Pelagic organisms may be attracted to or avoid lines and floats.	Ensure careful siting of farms to avoid rare or fragile habitats.	Garavelli and others (2024) Copping (2023)
	Tidal, ocean current				
	Ocean thermal energy conversion				
	Salinity gradients	n/a	n/a		
	Fixed offshore wind	Anchors, foundations and cables on the seafloor; mooring lines and floats/ platforms in the water column	Cables often buried, recovery of benthic habitats in weeks to months generally. Loss of soft-bottom habitats creates new hard-bottom habitats (can be beneficial for some organisms). Pelagic organisms may be attracted to or avoid lines and floats.	Ensure careful siting of farms to avoid rare or fragile habitats.	Maxwell and others (2022) Rezaei and others (2023)
	Floating offshore wind				
	Offshore floating solar photovoltaics		Blocking of wind and solar radiation, changes in turbulence and mixing within the water column, and the associated impacts on sediment resuspension near the seabed.		Schneider and others (2023)

Table 7 (*continued*)

Stressor	Offshore technology	Receptors	Potential effects	Mitigation	Citations
Oceanographic system changes	Wave	Wave height (decreased by energy)	At large-scale development, changes in circulation, wave height, sediment transport, possibly water quality and food web changes.	Monitor the situation and model potential changes.	Garavelli and others (2024)
	Tidal, ocean current	Water movement (altered by energy capture)			
	Ocean thermal energy conversion	Large volumes of cold deep-ocean water pumped to surface for mixing with warm tropical surface water, which may affect animals	The return to the deep ocean of cold water that has been pumped to the surface for heat exchange can cause thermal stress and local changes in oceanographic conditions.	Discharge cold ocean water below thermocline at depth to ensure return to appropriate density.	Copping (2023)
	Salinity gradients	Osmotic exchange of salt and freshwater from ocean and large rivers, which may affect animals	Changes in salinity resulting from brine disposal could alter water chemistry for nearshore organisms.		
	Fixed offshore wind	Flow around turbines bases will be altered, causing scour, which may affect animals	Changes in sediment transport and possibly in water quality and the food web.	Monitor the situation and model potential changes.	
	Floating offshore wind	Floating platforms will change surface flow, which may affect animals	At large-scale development: changes in circulation, wave height, sediment transport, and possibly in water quality and the food web.		Rezaei and others (2023)
	Offshore floating solar photovoltaics	Large platforms covering the sea surface, anchored to the seafloor, which may affect animals	At large-scale development: changes in circulation, sediment transport, shading, and possibly in water quality and the food web.		

Stressor	Offshore technology	Receptors	Potential effects	Mitigation	Citations
Entanglement	Wave	Large marine animals	Large marine animals might become trapped by mooring lines and cables.	Monitor for potential risk (applicable for floating devices only). Design turbines and supporting structures to minimize snagging risks and that are made of biodegradable materials.	Garavelli and others (2024) Bennun and others (2021) Copping (2023)
	Tidal, ocean current				
	Ocean thermal energy conversion				
	Salinity gradients	n/a			
	Fixed offshore wind	n/a			
	Floating offshore wind	Large marine animals	Large marine animals might become trapped by mooring lines and cables.	Monitor for potential risk. Design turbine and supporting structures to minimize snagging risks and use biodegradable materials.	Maxwell and others (2022) Bennun and others (2021) Copping and others (2023) Benjamins and others (2024)
	Offshore floating solar photovoltaics				
Displacement	Wave	Migratory, benthic and pelagic animals	Migratory animals may be forced from their routes, resulting in bioenergetic losses, increased predation and increased competition, potentially affecting population success. Benthic or pelagic animals may be kept from their habitats for feeding, shelter and reproduction.	Ensure sensible site selection to avoid sensitive foraging areas, protected areas (e.g. Natura 2000 areas in the European Union) and major migratory routes. Monitor for potential risk.	Greaves and others (2016) Garavelli and others (2024) Croll and others (2022)
	Tidal, ocean current				
	Ocean thermal energy conversion				
	Salinity gradients	n/a			
	Fixed offshore wind	Migratory, benthic and pelagic animals	Migratory animals may be forced from their routes, resulting in bioenergetic losses, increased predation and increased competition, potentially affecting population success. Benthic or pelagic animals may be kept from their habitats for feeding, shelter and reproduction.	Ensure sensible site selection to avoid sensitive foraging areas, protected areas (e.g. Natura 2000 areas in the European Union) and major migratory routes, and design installation spacing to allow for animal passage. Monitor for potential risk.	Croll and others (2022) Stoeber and Thomsen (2021) Bonar and others (2015) Benjamins and others (2024)
	Floating offshore wind				
	Offshore floating solar photovoltaics				

Table 7 (*continued*)

Stressor	Offshore technology	Receptors	Potential effects	Mitigation	Citations
Chemical releases	Wave	n/a as generally no petroleum products on-board	Spills and hazardous releases may cause injury or death to organisms from bacteria and phytoplankton to whales, altering habitats and ecosystem processes.	(Managed under hazardous waste and water quality plans in most nations.) Create realistic exposure scenarios to evaluate potential consequences and advocate improved regulatory frameworks (e.g. the Anemoi project).	
	Tidal, ocean current				
	Ocean thermal energy conversion	Ammonia or other heat exchange medium could leak into air or ocean, lubricants on board could leak			De Witte (2023) Galparsoro (2022)
	Salinity gradients	Use of chemicals at plant could leak into coastal waters			
	Fixed offshore wind	Lubricants for turbines could leak into ocean			De Witte (2023) Galparsoro (2022)
	Floating offshore wind				
	Offshore floating solar photovoltaics	Spills and use of plastics and other materials for operations and maintenance			

Source: Prepared by the writing team.

Abbreviation: n/a, not applicable.

6. Impact mitigation strategies

Amid deep concerns about the potential negative impacts of ORE installations, there is growing discussion about strategies for mitigating such impacts in order to achieve a biodiversity-compatible energy transition (Degraer and others, 2015; Marauhn and others, 2022; United Nations, 2024). There is also growing interest in the potential positive impacts of ORE deployments on marine ecosystems, such as offshore wind turbines fostering localized increases in marine biodiversity and small-scale fisheries limiting industrial-scale fishing activities. Even though uncertainties exist due to insufficient evidence (Andersson and Ahman, 2010), the present part of the subchapter outlines the existing mitigation strategies for marine renewable energies through specific risk scales, project timescales and spatial scales.

Understanding the effects of ORE on ecosystems is crucial for sustainable oceans (Board, 2023). However, many knowledge gaps, especially concerning the cumulative impacts of ORE over long distances and long periods, still need to be addressed, as regulations generally focus on one species or habitat at a time (Boyes and Elliott, 2014). Reconciling renewable-energy production with environmental protection using a precautionary approach requires a balanced strategy that integrates careful planning, robust regulations and adaptive management, and will involve finding compromises among and balancing the interests of different stakeholders. Such a strategy might include both spatial and technical solutions, as well as considerations related to the licensing of marine renewable projects and general compensation measures.

Mitigating the risks of offshore renewable energy (ORE) technologies is associated with the stage in the project life cycle that considers the duration and extent of the pressure exerted by the devices and the scale of the project (timescale of risk mitigation). It can include actions "before the fact" (i.e. avoiding impact), including design, deployment methods, operational strategies, maintenance methods and decommissioning actions (see table 8).

Table 8
Environmental impact mitigation strategies hierarchy throughout the offshore renewable energy life cycle

Mitigation hierarchy	Project phase	Key points and approaches
Avoid	Design and planning	Careful siting to avoid ecologically sensitive areas; marine spatial planning
	Operational strategies	Adaptive operations (e.g. turning installations off during species migration to enable safe passage)
Minimize	Deployment methods	Incorporating spatially explicit biodiversity data for considering potential cumulative impacts on biodiversity; designing devices that minimize disruption to natural water flow; employing advanced technologies and minimizing physical footprint; timing construction to minimize impact; routing construction vessels to minimize disturbances
Restore	Operational strategies	Implementing real-time monitoring systems and adaptive management; routing maintenance vessels to minimize disturbances; coupling adaptive operations with systematic environmental monitoring; minimizing vision-based impact (e.g. painting installations in monochromatic patterns to improve their visibility)
	Maintenance methods	Post-construction restoration of habitats, adding nature-inclusive design (or biodiversity-positive) elements e.g. structures with positive artificial reef effect designed to mimic natural characteristics of marine habitats
Offset	Operation and decommissioning actions	Sustainable transition to artificial reefs or industry tourism destinations; seawater reoxygenation; ecological compensation (including out-of-kind)

Source: Prepared by the writing team.

The impact mitigation hierarchy provides developers with a logical framework to address the potential negative impacts of development on biodiversity and ecosystem services. It is applicable to projects in any sector, including ORE, and is based on the sequential and iterative application of four actions: avoid, minimize, restore and offset. Several existing mitigation measures can be applied across all phases of an ORE project. The environmental impact mitigation strategies hierarchy, which considers optimal environmental impact minimization throughout the life cycle of ORE, is fundamental to best practice environmental management (Department of Climate Change and Water, 2023). Multiple decisions in the process of concession, installation and operation of ORE can help to avoid environmental impacts through sensible adaptive operations. Adaptive operations include site selection to avoid important seabird feeding areas, construction timing to minimize effects on spawning fish, and the routing of construction and maintenance vessels to minimize wildlife disturbances. Systematic environmental impact monitoring can provide the data necessary to devise and improve such adaptive operation strategies (see part 5). One measure that helps to reduce the environmental impact of offshore wind farms is a vision-based mitigation strategy of painting one of the wind-turbine blades black or using achromatic patterns on the blades. A study conducted onshore on Smøla in Norway has shown that such a mitigation strategy could reduce the annual bird fatality by 70% (May and others, 2020).

Other solutions under the impact mitigation hierarchy are aimed at restoring biodiversity. One example is artificial reefs, which are structures designed to mimic the natural characteristics of reefs or other marine habitats (Vivier and others, 2021). They can be strategically placed on the seabed as scour protection for energy infrastructure or in the vicinity of energy infrastructure to enhance biodiversity and restore food web complexity (Nauta and others, 2023). The structures serve as substrates for the attachment of various marine species and provide shelter and foraging opportunities for fish, crustaceans and other aquatic organisms. By fostering the establishment of diverse marine life communities, artificial reefs contribute to the overall health and resilience of offshore ecosystems. Lastly, impact mitigation measures can include efforts to offset environmental impacts and enhance biodiversity. Ecological compensation may also be "out-of-kind", meaning that it is provided in a different location from where the impact is made. One example could be the reoxygenation of seawater using oxygen that is a by-product of offshore green hydrogen production, but the technology is yet to be validated in offshore conditions.

All of the above-mentioned measures can be called nature-inclusive design or biodiversity-positive design, as they go beyond mitigating the impacts of the development and create a net positive impact. The increasing incorporation of such measures into offshore installations is becoming necessary for the successful application of offshore project developers to build wind and/or multi-source offshore energy parks, in line with non-price criteria in offshore wind tenders (for example, in the Kingdom of the Netherlands and the United Kingdom).

To ensure sustainable ORE development, mitigation strategies should be applied at multiple spatial scales in alignment with global, regional and local governance frameworks. Such strategies should integrate ecological and social considerations, particularly net marine gain, which is the net positive effect on marine biodiversity and ecosystems resulting from development projects.

International policies and frameworks provide a foundation for sustainable offshore energy development. Global instruments, such as the United Nations Convention on the Law of the Sea, which sets out the legal framework within which all activities within oceans and seas must be carried out, and initiatives such as the Sustainable Development Goals offer high-level guidance on biodiversity protection and climate action.

The transboundary impacts of ORE projects necessitate coordinated regional strategies to mitigate cumulative and shared effects. Regional environmental agreements, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), and cross-border cooperation can ensure that environmental standards are upheld across multiple jurisdictions. Environmental and social impact assessments and environmental impact assessments have been used for mitigating local impacts, applying a conservative approach to uncertainty and managing the cumulative effects of multiple projects in a single region to balance renewable-energy generation with environmental protection (Department of Climate Change and Water, 2023).

At the national and local levels, strategies should be tailored to mitigate the direct impacts of offshore wind projects. Such strategies should cover local innovative and sustainable pathways, including localized environmental impact assessments, marine spatial planning,

and the creation of marine protected areas (MPAs) to strategically manage the location of offshore energy infrastructure, minimizing impacts on critical marine habitats and species (Cordano and O'Dea, 2024).

7. Pathways to achieving sustainability: a vision for offshore renewable energy in 2030, 2040 and 2050

The present part of the subchapter provides a positive vision of future developments in the ORE sector. As the vision is based on predictions rather than evidence, the statements can be considered inconclusive.

By 2030, global and local decision makers will understand that a healthy ocean is the basis of a sustainable blue economy, and that they must move beyond a business-as-usual approach, simultaneously targeting economic development, ecological sustainability and human well-being. The ocean and the wind near the ocean's surface will be sustainable energy sources and could unlock new opportunities in the fight against climate change. Offshore energy development will be widespread, tools such as marine spatial planning and adaptive management (learning by doing) will be applied, offshore space will be used for multiple purposes and standardized quantitative assessments of the sustainability of the blue economy will be routine. Efforts to understand the interactions of offshore infrastructure with nature, design nature-inclusive offshore installations and deploy adaptive operations to ensure no harm will result in environmentally friendly installations that provide net marine biodiversity gain. Such efforts will also allow for the sustainable growth of ORE, avoiding and minimizing environmental impacts on the oceans.

By 2040, robust and sustainable business models and financing structures will have been developed that support economically sustainable commercial arrays of multiple types of offshore energy production, including offshore wind, wave and tidal, ocean thermal energy conversion, salinity gradient energy and floating solar. The design of global technology facilitation mechanisms will enable knowledge-sharing and access to science, technology and innovation in ORE technologies, helping to close the equity gap in access and enabling the roll-out of economically and environmentally sustainable technologies in developing countries.

By 2040, comprehensive quantitative socioenvironmental impact assessment tools will be widely applied by decision makers. This will result in fair assessments of the impacts – both local and global, both adverse and beneficial – of offshore energy on the oceans, as well as solutions that ensure energy justice and equity. The tools will be accessible, enabling the development of a sustainable blue economy on all continents while preserving the health of the ocean. New offshore installations worldwide will be focused on nature preservation and nature-inclusive design to protect and restore ocean biodiversity.

In 2050, the ORE sector, as part of a sustainable blue economy, will encompass multiple sectors and cross-sectoral activities related to the ocean and sustainability, including environmental sustainability, economic growth, social inclusion and equity. Increasing coordination and cooperation among different marine sectors will maximize the sustainable use of the oceans. The further promotion of ORE technologies in developing countries, including through concessional and preferential terms, mutual understanding and fair equity sharing, will result in a large-scale roll-out of sustainable offshore technologies all around the world.

By 2050, the surface of the oceans occupied by ORE will have increased tenfold compared with the time of writing, while yield will have increased fortyfold as technological advancements will have allowed for moving further away from shore. Offshore space will combine multiple sources of ORE (offshore wind, offshore floating solar or wave energy), aquaculture, hydrogen production and critical mineral recovery for the best use of ocean space. Nature-inclusive and environmentally friendly designs will have helped to avoid and minimize environmental impacts and increase biodiversity, thereby mitigating climate change and the biodiversity crisis.

Most Governments will have set renewable-energy goals, including the rapid scale-up of ocean energy technologies beyond offshore bottom-fixed wind, such as offshore floating wind, wave, tidal, offshore floating solar and ocean thermal technology conversion, resulting in 4 TW of ocean energy installed worldwide by 2050 and the limitation of global warming to 1.5°C.

8. Summary

Understanding risks related to ORE development can lead to designs, deployment methods, operational modes, maintenance tasks and decommissioning pathways that will minimize disturbances and harm to marine animals, habitats and ecosystem processes. Similarly, effective mitigation measures can be designed to minimize such risks. With the application of nature-based designs and operational modes, sustainable ORE development can support both climate change mitigation and biodiversity protection and improvements.

The increased uptake of ORE is expected to lead to change in coastal communities. Social equity should be prioritized in the consideration of the socioeconomic impacts. The rights of Indigenous Peoples and communities need to be foregrounded in the planned and continued development of ORE. Such development has a high potential for employment and local economic benefits, but investment in training, education and capacity-building is essential to overcome potential challenges. Assessing the impacts on coastal communities will require further research and will need to include both qualitative and quantitative analyses.

Knowledge gaps to be filled to enable the ORE vision, as outlined in part 7, are:

- Lack of research and innovation in new and emerging technologies, including those that will achieve hybrid solutions, grid integration, cost reduction, derisking, a circular economy for ORE components and a whole system approach.
- Lack of access, especially for developing countries, to accurate data or methodologies on resource characterization, environmental risks, application of nature-based social and economic assessments, life cycle assessments and technology assessments, and financial direction, as well as data on seabed conditions and living marine resources.
- Lack of access in many nations to knowledge and best practices for developing and implementing marine governance.
- Lack of qualified personnel in key government departments and agencies to deal with certain aspects of the project development life cycle, such as permitting.
- Lack of financing possibilities for ORE technologies in the least developed countries and limited financing possibilities in some of the emerging markets and developing economies, resulting in slow uptake of ORE technologies. Sustainable Development Goal target 17.6, which is to enhance knowledge-sharing and cooperation on and access to science, technology and innovation through a global technology facilitation mechanism, sets out a pathway for closing the gap in access to ORE technologies.
- Limited promotion of the development, transfer, dissemination and diffusion of ORE technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed, as set out in Sustainable Development Goal target 17.7.
- Lack of open access to data and information that follows Findable, Accessible, Interoperable and Reusable (FAIR), and FAIR, Artificial Intelligence Readiness and Reproducibility (FARR) principles, so that all decision makers and developers have access to the same high-quality information. Currently, large amounts of environmental data that could be open and readily available are being held as proprietary information.

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Subchapter 3B
Non-renewable energies: offshore hydrocarbons

Key points

- Offshore oil and gas production accounts for nearly one third of global oil and gas output, with deepwater and ultra-deepwater reserves driving recent exploration growth in regions such as the North and South Atlantic, West Africa and South-East Asia.
- Oil spills cause prolonged ecological disruption, with hydrocarbons persisting in food webs and affecting health, reproduction and population dynamics for a long time.
- Despite the growth in the volume of the world's oil production, there is a downward trend in the number of oil spill incidents and in the amount of oil released into the ocean thanks to improved regulation and technology.
- Production, transport and processing correspond to just under 15% of total energy-related greenhouse gas emissions.
- Technological advances in oil and gas are cutting costs, risks and emissions, but new remote-operation challenges and climate goals demand deeper efficiency and reduced demand.
- Offshore hydrocarbon development provides infrastructure growth, job creation and increased government revenues, yet its benefits are often unevenly distributed, leading to social tensions with local communities.

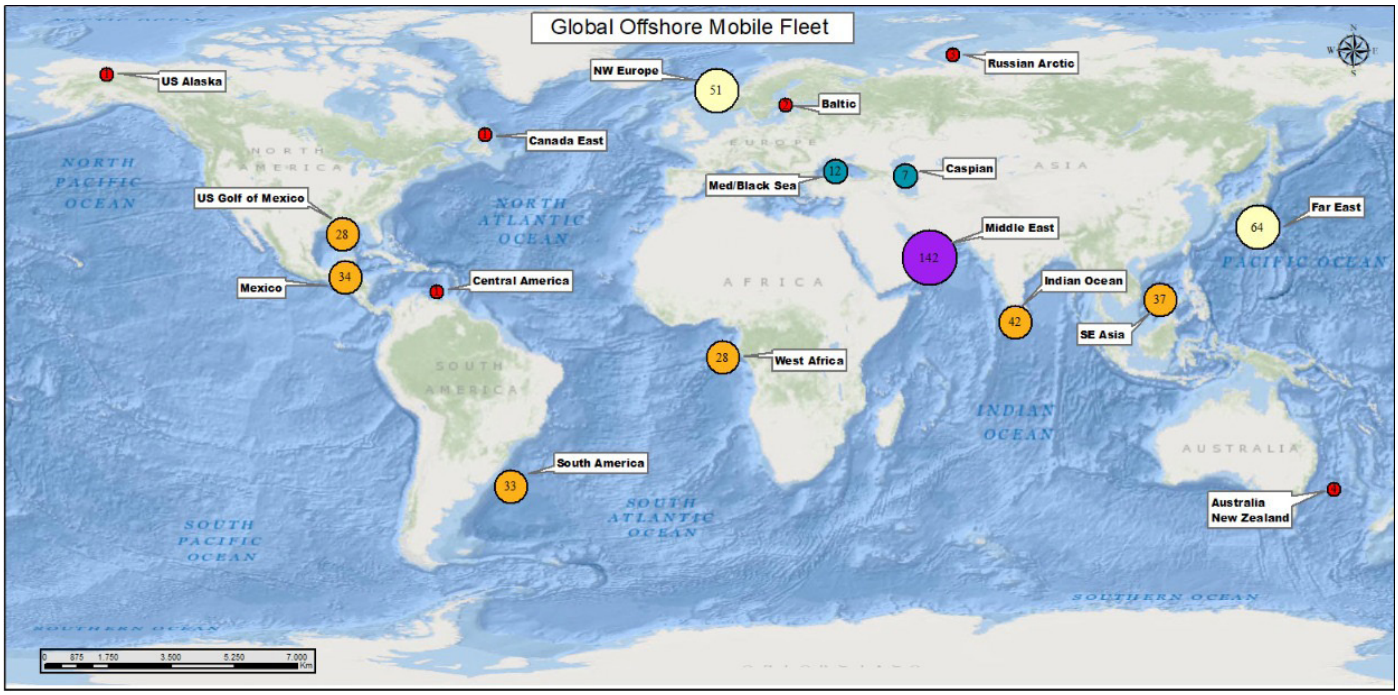
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1. Introduction

In the past 20 years, 30% of global oil production has been offshore. Of this, 43% has been concentrated in five nations: Saudi Arabia (13%), Brazil, Mexico, Norway and the United States of America. In addition, there are important developments under way in shallow-water and deepwater exploration projects in those geographical locations (see figure I).

In Asia, offshore hydrocarbon activity has expanded significantly. Indonesia and Malaysia are at the forefront of deepwater developments and offshore shelf expansion. Meanwhile, China is carrying out deepwater developments and Brunei Darussalam and Viet Nam are carrying out ultra-deepwater developments in the South China Sea. At the same time, Pakistan has been conducting offshore deepwater and offshore shelf exploration, and the shallow-water fields in India have been productive. Angola, Ghana, Mozambique and Nigeria have emerged as key players in the African offshore sector. The deepwater exploration prospects and results in West Africa have captured the attention of operators worldwide.

Figure I
Global offshore mobile fleet



Source: Prepared by the writing team.

In the Caribbean region, the discovery by Guyana of offshore oil and natural gas resources in the Guyana-Suriname Basin in the Atlantic Ocean is a game changer for Guyana, which has become the second-largest crude oil producer in Central and South America after Brazil.[1]

In the South Atlantic, although hydrocarbon volumes are not as significant as in the Caribbean, there is active exploration in both shallow and deep waters. Argentina and Uruguay are pursuing exploratory drilling in the Norte and Punta del Este basins. Hydrocarbon exploration has started on the plateau surrounding the Falkland Islands (Malvinas).[2]

Offshore exploration and production activities

The deeper the water, the higher the extraction costs. However, with high-resolution geophysical exploration technology, many major deposits have been discovered that are around 10 times larger than newly discovered

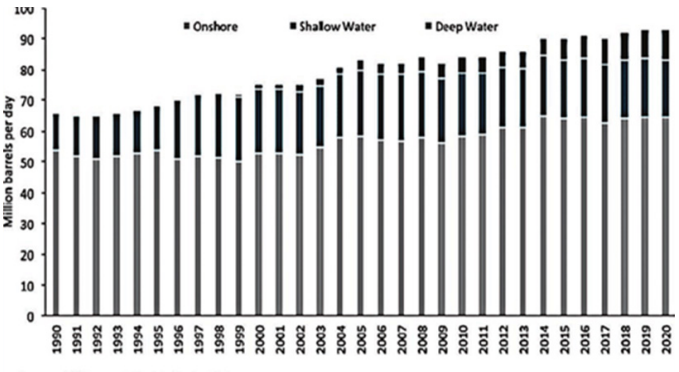
1 See www.eia.gov/todayinenergy/detail.php?id=62103.

2 A dispute exists between the Governments of Argentina and the United Kingdom of Great Britain and Northern Ireland concerning sovereignty over the Falkland Islands (Malvinas).

onshore fields, which makes deepwater and ultra-deepwater production an attractive prospect despite the higher costs (see figure II).

The deepwater and ultra-deepwater sectors are thus becoming ever more important: oil and gas extraction at water depths greater than 400 m is currently limited in scale, amounting to just 7% of global production.

Figure II
Cost of offshore water drilling by depth over time



Source: Prepared by the writing team, based on Infield Systems and BP Statistical Review 2014.

The region with the largest mobile offshore drilling units remains the Middle East, with just over 29% of the global fleet of shallow-water jackup rigs. The second- and third-largest regions are still, respectively, the Far East, with approximately 13% of the fleet, and north-western Europe, which has just over 10% of the fleet. South America has become more significant due to an increase in offshore drilling units in Brazil and Guyana. Northwestern Europe continued to be the leading region for semisubmersibles, with almost 40% of the global fleet. The Far East and South America round out the top three regions for semisubmersibles. Key information from data gathered in 2023 include the positive developments for global mobile offshore drilling units, which had a 79% equipment occupancy rate.

Production

The year 2024 marked the seventy-seventh anniversary of the first commercial offshore oil well drilled by a "mobile" rig out of sight of land. Since then, operators have moved progressively further offshore and deeper into the ocean in search of exploration and production opportunities, aided by rapid technological advances.

Offshore oil and gas production is conducted in many parts of the world, with the top-producing areas being the Middle East, the North Sea, Brazil, the Gulf of Mexico, the Gulf of Guinea and the Caspian Sea. In addition to resource development, some elements of the supply chain that used to be exclusively onshore – notably the liquefaction, storage and re-gasification of natural gas – are now increasingly taking place on specially designed offshore vessels.

Exploration activity has also been focused offshore. The largest recent oil and gas finds have all been in deep water (defined in an International Energy Agency analysis as a water depth greater than 400 m): deepwater finds have accounted for about 50% of the discovered conventional oil and gas volumes for the past 10 years. Some of these have been oil, notably the prolific "pre-salt" finds in Brazil, but more than half of all the new hydrocarbon resources discovered over the past decade have been gas, such as the Zohr and Leviathan gas fields in the Mediterranean, the Rovuma basin finds off Mozambique and the United Republic of Tanzania and other recent discoveries made off Côte d'Ivoire, Mauritania and Senegal in 2021 and 2024.

In recent years, amid low oil prices and the global coronavirus disease (COVID-19) pandemic, offshore oil production growth has been slow. However, as onshore oil and gas recoverable reserves have declined rapidly, offshore oil as a proportion of world oil production has actually increased.

In 2022, global crude oil production increased by a record rate of 5.4%, which is significantly higher than that growth rate in 2021 (1.6%) and the average growth rate from 2010 to 2019 (1.3% per year), in a context of global economic growth and progressive crude oil production adjustment by the Organization of the Petroleum Exporting Countries Plus (+0.4 million barrels per day each month until the phasing out of the 5.8 million barrels per day production adjustment).

Projections

Global deepwater oil resources are mainly concentrated in the middle and south sections of the Atlantic Ocean. Deepwater gas resources are relatively widely spread and mainly found in the deepwater basins in the northern part of Atlantic Ocean, off East Africa, in the Neo-Tethys region and around the Arctic Pole.

There will be six domains for the future oil and gas exploration in global deepwater basins: two "old" domains, which refer to, first, the offshore deepwater basins in the Atlantic and, second, the offshore deepwater basins of the Neo-Tethys structural domain, where the exploration degree is relatively high and the potential is still great; and four "new" domains, which refer to pre-salt and ultra-deepwater basin formations, offshore deepwater basins surrounding the North Pole, and offshore deepwater basins in the west Pacific Ocean. The new domains will be the main fields of deepwater oil and gas exploration in the future.

2. Pressures and impacts

Environmental impacts

Offshore oil and gas exploration can cause significant environmental impacts. These impacts can be acute, resulting from spills and blowouts, or chronic, often from routine discharges over the long term. They can also result from transport processes, such as pipeline breakage or ship accidents. Natural seepage can also be substantial in some areas, contributing to increased background levels.

Key impacts include:

(a) Oil spills and hydrocarbon release
- **Acute impacts:** large oil spills result in immediate harm to marine life, coating animals and plants, impairing their ability to breathe, move and feed (Beyer and others, 2016).
- **Chronic impacts:** the continuous release of smaller amounts of hydrocarbons and chemicals can lead to bioaccumulation, disrupting the food chain and affecting species over time.

(b) Chemical discharges (drilling mud and drill cuttings)
- **Acute impacts:** drilling mud, often laden with toxic chemicals, can smother benthic (seafloor) organisms and contaminate the surrounding water, harming fish, corals and other marine life.
- **Chronic impacts:** persistent exposure to low levels of toxic chemicals, such as heavy metals in drilling fluids, can lead to reproductive and growth issues in marine species.

(c) Noise pollution (seismic surveys)
- **Acute impacts:** loud blasts from seismic surveys can cause physical harm to marine mammals, especially those reliant on echolocation (e.g. whales, dolphins), leading to temporary or permanent hearing loss.
- **Chronic impacts:** continuous noise pollution disrupts communication, migration and mating behaviours in various marine species, potentially reducing population levels over time.

(d) Platform installation and decommissioning
- Offshore oil and gas platforms generate noise during their continuous operation over years of active exploitation of each oilfield. An assessment of operation noise of six floating platforms off the coast of Australia has shown that median radiated levels do not depend on platform size or operation mode, and are in the order of 181 dB re 1 μPa in the band 20–2500 Hz (Erbe and others, 2013).

(e) Produced water discharge
- **Acute impacts:** produced water contains oil, heavy metals and naturally occurring radioactive materials, which can be toxic if released in large quantities, especially in shallow waters.
- **Chronic impacts:** the constant release of produced water contaminates the marine environment, leading to chronic exposure for marine species that results in developmental, reproductive and genetic harm (Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission), 2021).

(f) Habitat alteration and physical disturbance
- **Acute impacts:** activities such as seabed drilling and pipeline installation disrupt habitats, displacing or killing benthic organisms and damaging coral reefs and seagrass beds.
- **Chronic impacts:** ongoing physical disturbance from infrastructure maintenance, anchor placement and drilling activities can gradually degrade fragile marine ecosystems, leading to loss of biodiversity.

(g) Air pollution and atmospheric deposition
- **Chronic impacts:** flaring and other emissions release pollutants (e.g. sulfur oxides, nitrogen oxides and greenhouse gases) that can be deposited into the ocean, leading to acidification and eutrophication, which harm marine life and coral reefs.

Overall, both acute and chronic discharges from offshore oil and gas exploration create lasting and cumulative effects on the marine environment, affecting biodiversity, food webs and the health of coastal and oceanic ecosystems.

Seismic surveys

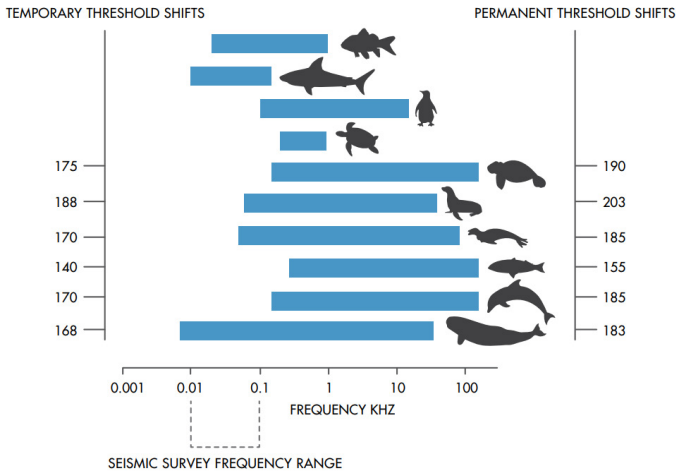
Seismic exploration is a technique based on the analysis of the reflection of acoustic waves off of subsurface layers of various density and is used for estimating layer thickness and geotechnical properties and, ultimately, for detecting large oil and gas reservoirs.

Seismic signals can be heard thousands of kilometres away from the area being surveyed. Moreover, the emitted power is concentrated in the frequency band shared with a broad range of cetaceans, including baleen whales (mysticetes), which furrow the ocean in long migration paths. Seismic survey signals heavily interfere with their orientation, communication and feeding habits (see figure III).

Overall, impacts on marine species depend on the extent of water sound propagation, noise frequency, noise duration and distribution over the habitat, species sensitivity and spectral hearing. Zooplankton species, mostly copepods, exhibit decreased abundance and significant mortality under air gun signal (McCauley and others, 2017). In the case of fish and cephalopods, behavioural responses have been observed up to 5 km away from the seismic survey, expressed as changes in-depth distribution, schooling behaviour and startle responses to high-level sounds. Fishers experience these impacts as reduced catch rates (40–80%) and decreased abundance in the vicinity of seismic surveys. Seismic surveys may also affect marine fish eggs and larvae, causing decreased egg viability, increased embryonic mortality or decreased larval growth. Prolonged stress and displacement from habitats have been seen in seals, sea lions and walrus populations. As the noise footprint of seismic surveys is relatively large in deep waters, marine mammals, mostly cetaceans, are highly affected (Kavanagh and others, 2019). Impacts include stress increase, behavioural changes, hearing loss and even death by drowning or stranding.

As a result of the documented impacts of seismic surveys on marine fauna, several countries have taken steps to minimize such impacts. The United Kingdom of Great Britain and Northern Ireland introduced regulations formulated by the Joint Nature Conservation Committee, which gave rise to mitigation methods such as the use of the lowest practicable volume throughout the survey, the reduction of high-frequency output, the delineation of exclusion zones, the adoption of "soft-start" principles in sound emission, and the visual and passive acoustic monitoring of marine mammals during the survey.

Figure III
Temporary and permanent impacts of seismic surveys on marine fauna (after Purdon, 2018)



Source: Prepared by the writing team.

Impacts of offshore installation disasters

Oil spills occur frequently in the marine environment, sometimes with devastating socioenvironmental consequences. Marine oil spills are the result of shipping-related accidents or accidents in offshore fixed installations. Spills from fixed infrastructure can involve "live" crude oil, presenting distinct challenges in terms of environmental impact and response strategies. The Ixtoc I and the Deepwater Horizon oil well blowouts in the Gulf of Mexico in 1979 and 2010, respectively, were two of the largest spills of oil in the history of marine oil drilling operations, having released 3.5 million and 4.9 million barrels of oil, respectively, before being contained.

The Deepwater Horizon spill was unique in that it was the first-ever significant deepwater well blowout with live oil (i.e. a mixture of dissolved natural gas and oil) (Passow and Overton, 2021). Leaking at a depth of 1,500 m below sea level, the Deepwater Horizon well blowout showed that remote and largely unknown deep-sea ecosystems are susceptible to the impacts of offshore drilling accidents. Damage to offshore infrastructure, such as platforms or pipelines, that results in accidental oil leaks may also be caused by extreme weather events, mudslides and seafloor erosion.

In 2004, Hurricane Ivan caused a massive mudslide on the Gulf of Mexico seafloor that sank an entire drilling platform. The site had been leaking an average of 19–108 barrels of oil per day for 15 years until an underwater containment system was installed in 2019 (Mason, Taylor and MacDonald, 2019). In the wake of Hurricane Ida in 2021, one of the largest reported spills (located off Port Fourchon, Louisiana, United States) was attributed to oil leaking from decommissioned pipelines that had been left on the seafloor (Arslan and others, 2023). Assessing the environmental damage and the recovery of ecosystems after the spill has been problematic due to a lack of baseline (pre-spill) data and delays in deploying – or a complete absence of – scientific surveys. Deepwater Horizon is the best studied oil spill in history due to extensive research efforts initiated during the spill, including the 10-year Gulf of Mexico Research Initiative. The Initiative terminated its active research in June 2020, having produced an unprecedented understanding of the impact of the Deepwater Horizon oil spill on the environment and public health in the Gulf of Mexico.

Recent breakthroughs in drilling technology are propelling the growth of deepwater and ultra-deepwater exploration and production, which currently dominate the offshore drilling market. Technological advancements in subsea robotics, real-time monitoring and sensors, and the use of blowout preventers have increased operational safety, even if the risks associated with deepwater drilling cannot be eliminated entirely. In 2023, the oil and gas reserves discovered in deep and ultra-deep waters accounted for 62% of the total offshore oil and gas reserves (Wen and others, 2023). These reserves are mainly located in deepwater basins in the Atlantic Ocean (including in the Gulf of Mexico and off the coast of Brazil, Norway and West Africa), the East African continental margin, the western Pacific Ocean (including in the South China Sea and off the coast of South-East Asia), the North West Shelf of Australia, the Eastern Mediterranean Sea and the Arctic (including in the Barents Sea). The current world record water depth for an oil and gas well is held by the Ondjaba-1 well off the coast of Angola, reaching a depth of 3,628 m in 2021 (Enverus, 2024). The deepwater and ultra-deepwater drilling market is expected to grow significantly in the coming years due to the increasing global demand for oil and natural gas. It follows that the risk in the future of an oil spill in deep waters akin to the Deepwater Horizon spill is also increasing.

Persistence of hydrocarbons in the marine environment

The severity of the impact of an oil spill depends on a variety of factors, including the physico-chemical properties of the oil itself, the quantity of oil spilled, external conditions such as the prevailing climatic and sea conditions, and the types of habitat affected. Oil spill residues persist for decades in certain low-energy and often hypoxic environments, such as coastal mangrove forests, salt marshes and deep-sea sediments. Partially weathered oil and high molecular weight polycyclic aromatic hydrocarbons from the Ixtoc I oil spill in 1979 are still present in mangrove forests and sediments underlying more than 500 m of water in the southern Gulf of Mexico, 40 years after the incident (Radović and others, 2020; Lincoln and others, 2020). Similarly, recalcitrant oil residues from the Deepwater Horizon spill in 2010 were still detected eight years after the spill in deep (Diercks and others, 2021) and coastal marsh sediments of the northern Gulf of Mexico (Turner and others, 2019). In the Arctic, where oil degradation is limited by low temperatures and the short duration of Arctic summers, residual oil is still present in beach sediments 40 years after an experimental oil spill (Schreiber and others, 2023). To compare, in the warm and aerated sandy beaches of the Gulf of Mexico, stranded oil from the Deepwater Horizon spill was degraded within a year (Huettel and others, 2018). Coastal wetlands and deep benthic environments can be considered chronic "reservoirs" of oil residues and a continued source of toxicants to living organisms for decades (Murawski and others, 2023; Turner and others, 2019). This may result from the resuspension of contaminated sediments by physical processes (e.g. bottom currents, storms), burrowing behaviour of certain taxa or feeding on benthic infauna. In contrast, weathering processes (e.g. photo-oxidation, spreading, dispersion, dissolution, evaporation, biodegradation) acting on oil in open waters lead to the removal of hydrocarbons from the water column within a relatively short period of time – in the case of Deepwater Horizon, as short as a few weeks after the spill was contained (Liu and others, 2016; Ward and others, 2018). The role of biodegradation is crucial in deep waters as it is the only way to remove oil from these environments (Scoma and others, 2017). Microbial hydrocarbon oxidation data under high hydrostatic pressure conditions are lacking owing to methodological challenges and the difficulty of

obtaining samples (Marietou and others, 2018; Nguyen and others, 2018; Antoniou and others, 2022). These data are urgently needed to improve understanding of the interplay between temperature and hydrostatic pressure on biodegradation in view of the rapid expansion of oil and gas drilling into deeper waters (Kostka and others, 2020).

Fish in their early developmental stages have been shown to be particularly vulnerable to crude oil exposure. Several studies have demonstrated that such exposure is toxic to the development of the heart, causing cardiotoxicity and oedema in fish embryos.

Exposure to oil and concentrations of total polyaromatic hydrocarbon as low as 0.1 µg per litre have been shown to cause developmental toxicity in haddock (*Melanogrammus aeglefinus*) (Sørhus and others, 2023).

The effects on juvenile haddock were demonstrated after exposure to different polycyclic aromatic hydrocarbon types extracted from produced water and crude oil (dominated by three-ring polycyclic aromatic hydrocarbons). DNA adducts, the most sensitive biomarker, were detected in tissue using ^{32}P postlabelling analysis, but it was not possible to distinguish between the DNA adducts from the different sources (Meier and others, 2020).

Impact of oil spills

All biological systems, including those in environments where oil is not retained for a long time, show prolonged impacts due to cascading effects that influence functional connections within and between communities (Halanych and others, 2021). For example, toxicants derived from the Deepwater Horizon oil spill (polycyclic aromatic hydrocarbons) were present in eggs of mesopelagic fish at levels above those known to cause sublethal effects six years after the spill (Romero and others, 2018) as a result of food web incorporation and maternal transfer. Prolonged exposure to polycyclic aromatic hydrocarbons has been associated with negative health effects, including decreased body condition, decreased energy reserves and susceptibility to diseases, that may have serious consequences for long-term population viability (Snyder and others, 2019). Fish species affected by the Deepwater Horizon spill, such as tilefish, groupers and red snapper, showed elevated polycyclic aromatic hydrocarbon concentrations in their tissues, external skin lesions and other morphological and histopathological symptoms consistent with continued chronic exposures (Pulster and others, 2020; Snyder and others, 2019). The chronic effects from lingering oil in sea otters and harlequin ducks persisted for at least two decades after the Exxon Valdez oil spill in Alaska and had a larger influence on population dynamics over the long term than the acute effects of the spill (Esler and others, 2018). Upper trophic levels exhibit considerable delayed impacts and slower rates of recovery due to smaller population sizes, longer generation times and bioaccumulation of toxicants in their tissues. Killer whale pods that were affected by the Exxon Valdez spill have not yet recovered, but this is more likely due to demographic factors rather than long-term toxicity effects (Esler and others, 2018). Another characteristic example is the population of bottlenose dolphins living within the footprint of the Deepwater Horizon oil spill. This population experienced high mortality rates and impaired reproduction rates in surviving individuals from 2011 onwards (Kellar and others, 2017; Murawski and others, 2021). In contrast, lower trophic levels, such as zooplankton, show increased resilience because of shorter generation times and high fecundity that allow faster adaptation to altered environmental conditions (Halanych and others, 2021; Patterson and others, 2023). Deep-sea and mesopelagic environments show less resilience than shallow-water environments. This is because deep-sea organisms generally exhibit a slower pace of life than their shallower-water counterparts owing to the low temperatures and low energy supply in the deep benthic and pelagic realms (Cordes and others, 2016). Extensive and persistent declines in abundance of both mesopelagic and bathypelagic fishes and macrocrustaceans appear to be ongoing in the Gulf of Mexico a decade after the Deepwater Horizon spill (Sutton and others, 2022).

Disruption of ecosystems

Oil spills have major impacts on the marine environment and ecosystem, mostly affecting fisheries, wildlife and coastal and marine habitats (El-Sayed and others, 2021). The ecological impacts appear directly related to the dynamics of the spill, including oil characteristics, spill volume, release rate, trajectories and response action (Baron and others, 2020). Impacts also depend on the vulnerability of affected ecosystems and individual species, and can affect species' natural mortality and predators (Zhang and others, 2019). Ambient temperature affects oil viscosity, which controls oil spreading and degradation rates, while incident solar radiation affects the phototoxicity of organisms. The environmental impacts are directly related to oil persistence. Oil may remain in

the water column for as long as half a year, but is usually diluted and sedimented to background levels much more rapidly (Teal and Howarth, 1984). The physical characteristics of oil and its toxic chemical constituents can cause major effects on marine life, affecting critical processes such as feeding, breathing and thermoregulation, and can eventually lead to physical suffocation. The absorption of chemical components into organs, tissues and cells may result in poisoning. Acute toxic effects from the ingestion or inhalation of oil, as well as smothering, drowning and hypothermia affect the mortality of marine invertebrates, mammals and seabirds (Peterson and others, 2003). However, even marine organisms far away from the spillage may also be affected, either directly through exposure to oil or indirectly through the trophic web (i.e. by ingesting affected prey (Olsen and others, 2019)). In the pelagic ecosystem, planktonic copepods exposed to oil may experience immediate death, acute toxicity, decreased feeding, delayed egg production, sluggish hatching rates, decreased swimming speeds and reproductive abnormalities. However, as plankton are plentiful and naturally experience extremely high mortality rates, plankton deaths occurring after a spill rarely have long-term effects (International Tanker Owners Pollution Federation Handbook (ITOPF), 2023/24). Heavier oils and worn residues may affect the benthic ecosystem. Although they are not always lethal, they can have short-term consequences such as narcosis and tissue tainting.

Studies have shown that although individual marine organisms can suffer significant harm due to coating and oil ingestion, populations tend to be resilient (Murawski and others, 2023). Ecosystems may recover between 2 and 10 years after the incident, even when facing significant disturbances and mortality.

Impact on reproduction and development

Adult fish typically have greater resistance to oil effects than eggs and larvae, which may be more vulnerable (Singh and others, 2020). Fish are able to sense unfavourable water conditions and swim away, resulting in declining fish stocks in offshore and coastal waters after oil spills. In shallow or confined waters, very high, localized concentrations of dispersed oil may cause mass mortalities. Adult fish exposed to high oil concentrations experience acute cardiotoxicity, heart failure, decreased swimming speeds and breathing rate reduction.

Sublethal effects

Numerous investigations have demonstrated the sublethal effects of polycyclic aromatic hydrocarbons on fish, including decreased rates of growth and feeding, genetic damage, mortality of fish eggs and larvae, increased susceptibility to starvation and incapacity to flee predators (Langangen and others, 2017). The sublethal effects of oil exposure on marine organisms, including marine mammals, can include enhanced or suppressed cell proliferation, decreased phagocytosis and induced cell apoptosis, eventually resulting in disease, decreased resilience, community structure changes, mortality and, ultimately, population declines (Lee and others, 2018). After the Deepwater Horizon oil spill, demersal fish species presented pathological changes in the skin and suffered from increased incidences of bacterial infections, including skin lesions (Murawski and others, 2014). In addition, the body weights, germinal epithelium thickness, oocyte diameters and gonadal somatic indices of killifish at the oil-affected sites were lower than those from non-affected sites (Carr and others, 2018).

Impacts on fishing

Fisheries and mariculture resources could suffer significantly from oil spills (Andrews and others, 2021). Physical contamination can impede access to fishing sites or foul gear, which affects stocks and business operations. The loss in fishery production resulting from direct mortality, habitat loss or access restriction due to harvesting bans and closures typically affects commercial fisheries and aquaculture enterprises. A decrease in market demand due to concerns about contaminated products also results in losses. To speed up the compensation process, all fishery damage must be recorded and, if feasible, backed up by proof. This frequently calls for exacting scientific sampling and analysis. Accurate estimates of spill-related damages require comparing post-spill recovery against pre-spill fishing (ITOPF, 2023). However, it is frequently challenging to distinguish between the consequences of an oil spill and other elements, such as industrial pollution and overfishing (ITOPF, 2023).

Although the financial impact is typically less severe, oil spills can pose a serious threat to other marine-based industries such as port operations and sea-based transportation, and industries that depend on saltwater for regular operations such as power plants and desalination facilities (Chang and others, 2014; ITOPF, 2023).

The aftermath of an oil spill, including clean-up efforts, can cause disruptions to other forms of coastal industry, including shipyards, ports and harbours (ITOPF, 2023). In addition, reduced disposable income and reduced market demand may result in pure economic losses for the larger economy (Dahi Taleghani and Tyagi, 2017).

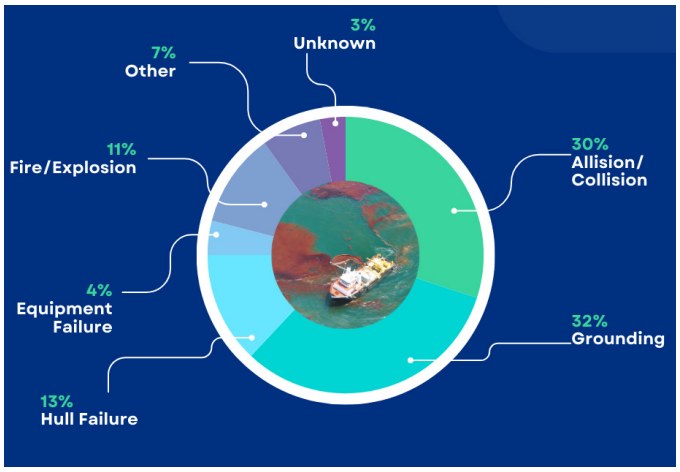
Oil spill from tanker incidents

The term "oil spill" refers to the pollution caused by the unintentional release of liquid petroleum hydrocarbons into the maritime environment. Oil spills can be caused by human error, fatigue loading or explosions; damages in underwater oil pipelines; or ship collisions, bunkering, groundings and hull failures. According to ITOPF (2023), over the past 50 years, large spills were primarily caused by groundings (32%) and allisions or collisions (30%) (see figure IV). Despite the growth in the volume of the world's oil trade (ITOPF, 2023), there is a downward trend in the number of oil spill incidents and the amount of oil released from tankers worldwide (Chen and others, 2019).

The human factor accounts for at least 80% of tanker accidents worldwide (Wan and Chen, 2018) and is related to overwork, insufficient experience in specific operations, inadequate communication or outdated navigational charts.

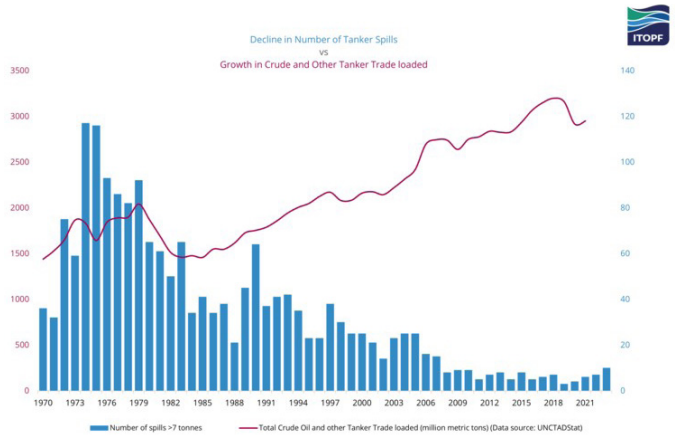
A database maintained by ITOPF that includes tank vessels (combined carriers, floating production storage and offloading vessels, and barges) shows that, over the past 50 years, there has been a marked downward trend in the frequency of oil spills larger than 7 tons (see figure V). The average number of spills per year was approximately 79 in the 1970s and has decreased by over 90% to 6.3 in the 2010s and has remained at the same level for the past decade. This trend has accompanied an increase in oil trading over the same period (see figure V).

Figure IV
Causes of large tanker spills (>700 tons) in the period from 1970 to 2022



Source: Prepared by the writing team.

Figure V
Number of spills (>700 ton) from tankers compared with the growth in crude and other tanker trade in the period from 1970 to 2021



Source: Prepared by the writing team, based on data from ITOPF and UNCTADStat.

3. Socioeconomic considerations

The offshore hydrocarbon industry's operations often intersect with the social and environmental concerns of local communities, leading to conflicts and challenges in securing public acceptance (Sovacool, 2022).

Such conflicts can arise from a range of factors, including the perceived inequitable distribution of economic benefits, environmental degradation and the disruption of traditional livelihoods. One of the primary sources of conflict is the uneven distribution of the economic gains from offshore hydrocarbon activities. While these activities can bring employment opportunities and revenue to the region, the local communities may feel that they are not receiving a fair share of the benefits (Sovacool, 2022). This can lead to resentment and a sense of marginalization, fuelling social unrest and resistance to the industry's presence.

Environmental concerns often clash with the industry's pursuit of economic growth, leading to protests, legal challenges and a general lack of public trust. In response to such challenges, the offshore industry has sought to improve its social and environmental performance through various strategies, such as community engagement programmes, environmental impact assessments and corporate social responsibility initiatives.

However, the success of such efforts has been mixed, and a more comprehensive and collaborative approach is often required to address the underlying social and environmental issues. Fostering public acceptance of offshore hydrocarbon activities requires a delicate balance between economic development, environmental protection and social equity. By prioritizing inclusive and sustainable practices, the industry can work to build trust with local communities and mitigate the potential for conflicts (Sovacool, 2022).

Communities reliant on hydrocarbon activities: economic dependence, infrastructure development, social impact, environmental concerns

A review of literature by Andrews and others (2021) showed varied economic outcomes with regard to communities' reliance on the offshore hydrocarbon industry. Oil discovery usually initially sparks optimistic hopes for economic development and improved livelihoods (Andrews and others, 2021; Stergiou, 2022). Generally, there is an increase in public expenditure, which can improve social welfare benefits and often results in infrastructure development, including improved car, bus and aeroplane access to coastal towns or cities, as well as increased maritime infrastructure and traffic. This further results in greater mass tourism due to access to areas that can sometimes previously have been remote (Andrews and others, 2021; Stergiou, 2022). It can also result in job creation on oil rigs and in surrounding industries and in the creation of a cycle of spending that may boost local industries and economies. In addition, oil discoveries provide Governments with the opportunity to impose and reap benefits of additional taxes, such as corporate income tax, which can then be equitably distributed (Stergiou, 2022). Some studies have found that a key factor in determining whether local communities will economically benefit from the hydrocarbon industry is whether government policies mandate the use of local goods and services by the industry. Such policy action has seen improvements in oil sector economies in Angola, the Bolivarian Republic of Venezuela, Ghana, Nigeria and Norway (Andrews and others, 2021).

However, offshore hydrocarbon development can result in a "double deprivation" for coastal communities, as they may be excluded both from utilizing the ocean as a resource to sustain their livelihoods and from employment by the offshore hydrocarbon industry (Andrews and others, 2021). Evidence shows that, where the offshore hydrocarbon industry is predominantly operated by foreign companies, impacts for local communities are less likely. In Ghana, for example, there are few employment opportunities for local people because the industry benefits are offshore and capital- and technology-intensive (Andrews and others, 2021).

The offshore hydrocarbon industry can have significant negative impacts on small-scale fishers. Hydrocarbon infrastructure, pipelines and exclusion zones created around rigs affect the areas that are accessible for fishers from local communities (Andrews and others, 2021; Bennett and others, 2021). Oil development has resulted in a lack of access to areas that have historically been used for fishing, loss in fishing time, destruction of fishing gear and spatial displacement of small-scale fishers and Indigenous Peoples (Andrews and others, 2021; Bennett and others, 2021). Evidence from global studies also indicates that hydrocarbon pollutants in the marine environment leads to a reduction in fish populations (Ite and others, 2024). Studies have shown dissatisfaction among fishers in coastal communities in Ghana, Peru and the United Kingdom (Andrews and others, 2021). Protests and conflicts between small-scale fisher communities and the oil industry have been recorded in various places globally, such as Argentina, the Gulf of Mexico and Peru (Andrews and others, 2021; Morea, 2023).

Some offshore hydrocarbon projects require shore-based processing facilities to be built. Such facilities have impacts on coastal communities that should also be considered. The construction sites provide jobs in local areas. However, because their pay rates are higher than local jobs, this can result in a loss of workers from low-paid but essential local jobs. An increased number of workers from outside the area with higher pay can cause increases in the value of property, land and everyday commodities, negatively affecting existing local economies (United Nations Environment Programme Finance Initiative, 2022). In addition to posing environmental challenges, these large-scale developments may

inhibit access to coastal areas, limit established economic activities such as fishing and tourism, and block access to sites of cultural significance and recreational areas (United Nations Environment Programme Finance Initiative, 2022; Bennett and others, 2021).

The cultural identities, value systems and traditions of rural communities may be undermined by oil development. For example, in the Niger Delta, a cultural new year's tradition where women ceremonial bathe in coastal streams has been phased out because of oil spill contamination (Ite and others, 2024). There has been substantial research on environmental injustices caused by the oil industry, which has provided evidence of long-term health-related issues. Oil rigs and pipelines may release toxins for years after their operations have concluded (Bennett and others, 2021).

The initial hope for economic progress that oil discovery brings often goes unrealized, particularly for communities that are situated adjacent to the resource. In the substantial literature reviews conducted by Andrews and others (2021) and Bennett and others (2021), it was reported that oil cities or countries often failed to improve, and sometimes worsened, the lives and economic realities of their populations.

Piracy

Piracy has emerged as a significant threat to the offshore oil and gas industry, posing risks to the safety and security of personnel, as well as the operational and financial stability of the companies involved. The fact that offshore facilities are remote and often poorly secured makes them vulnerable targets for criminal activities. The Gulf of Guinea is a global hotspot for such incidents.

The presence of offshore hydrocarbon activities can contribute to the marginalization of coastal communities, leading to resentment and a sense of disenfranchisement, which can fuel the rise of piracy and other criminal activities.

In response to this challenge, the United Nations and various regional organizations have implemented a range of strategies to combat piracy in the offshore domain (United Nations Environment Programme Finance Initiative, 2022). These strategies include enhanced maritime security measures, improved surveillance and intelligence-sharing, and collaborative efforts with local law enforcement agencies.

The social aspects of offshore hydrocarbon activity, particularly in relation to piracy, require a nuanced understanding of the complex interplay between economic, political and cultural factors.

4. Sector-relevant governance

The great advances in the oil and gas industry refer to the use of technology to reduce risks, costs and impacts. Automation and remote operations allow the reduction of personnel on board and consequently of support costs, such as transportation, lodging and meals (International Association of Oil & Gas Producers (IOGP), 2018), and of greenhouse gas emissions. There has been a rise in the use of remote technologies, such as uncrewed surface vessels, drones, robotics, remotely operated vehicles and autonomous underwater vehicles.

While removing personnel from platforms and vessels may reduce risk of personnel accidents and injuries, it prevents the observation of the physical operations, including sight, vibrations, smells and sounds, increasing the reliance on information systems and clues from the digital environment (European Safety and Reliability Conference (ESREL), 2023).

Remote operation may vary from remote control, engineering, maintenance and monitoring to full operation of the site. Implementing remote functions creates additional risks, including information security risks, as well as risks involving the ability to enforce control of work policies, to define the division of functions and responsibilities between remote and local operations and to assure the reliability of remote communications. Along with traditional risk analysis, these new risks shall be considered during the design phase of the operating philosophy (IOGP, 2024).

Another huge challenge imposed on oil and gas exploration and production is to reduce greenhouse gas operations emissions to achieve the world's climate goals. In 2022, oil and gas consumption was responsible for around half of the total energy-related CO_2 emissions, equivalent to over 18 $GtCO_2$ (International Energy Agency, 2024a, 2024c).

Production, transport and processing correspond to just under 15% of total energy-related greenhouse gas emissions. To reduce scope 1 and 2 emissions, the oil and gas industry must eliminate all non-emergency flaring, adopt energy-efficient solutions, electrify upstream facilities with low-emissions electricity, equip oil and gas processes with carbon capture, utilization and storage and, most importantly, reduce methane emissions (International Energy Agency, 2024b; World Economic Forum (WEF), 2023).

Under the Global Methane Pledge, 158 countries have agreed to reduce methane emission by 30% below 2020 levels (Global Methane Pledge, 2024). With the necessary financial resources and gas market conditions, methane abatement technologies could be implemented without added costs given the value of recovered gas (WEF, 2023). Zero Routine Flaring by 2030, another voluntary initiative, has been endorsed by 36 countries and 58 oil and gas companies (Zero Routine Flaring by 2030 (ZRF), 2024).

To achieve net-zero emissions by 2050, the global average emissions intensity of oil and gas production must fall by more than 50% between 2022 and 2030 to a number close to the emissions intensity of the best operators today. However, operational efficiency and new technologies are not enough; to achieve net-zero emissions, oil and gas demand must decline by more than 5% each year on average up until 2050 (International Energy Agency, 2024b).

According to WEF, in the five enablers for readiness – technology, infrastructure, demand, policy and capital – the oil and gas industry is the most ready for the energy transition. The industry's technology readiness level is classified as stage 4 out of 5 (WEF, 2023).

5. Sustainability pathways

Mitigation measures and environmental standards are in place in many regions to reduce the impacts of offshore hydrocarbon activities.

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Chapter 4
Tourism

Key points

- Coastal and ocean tourism can support all pillars of sustainable development.
- Coastal and ocean tourism relies heavily on ocean and marine ecosystem health while also contributing to various negative impacts on natural and cultural resources. Sustainable tourism remains difficult to achieve due to data gaps concerning the hidden costs of tourism and the value of natural and cultural capital.
- Visitor arrivals create opportunities for data collection, dissemination of information regarding sustainability, and the harnessing of tourists' willingness to contribute to sustainable outcomes.
- Transitioning the tourism sector towards a more sustainable paradigm will require significant political will and leadership to shift away from the prioritization of low-cost mass tourism and towards the adoption of a more holistic view of tourism success that promotes reinvestment into the local community, culture and environment.

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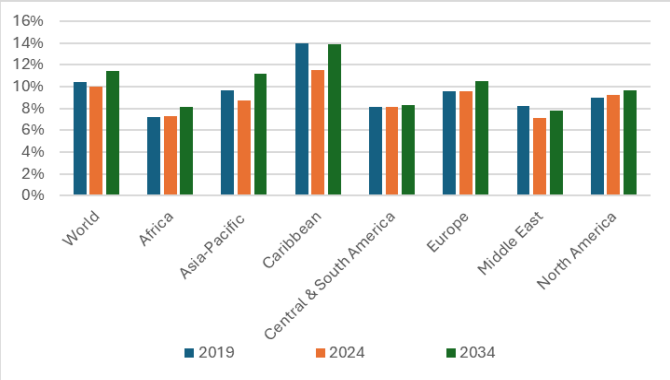
1. Introduction

The purpose of the present chapter is to provide an overview of the scope and extent of coastal and ocean tourism, highlight the pressures and impacts of tourism on ecosystems and human well-being and provide alternative pathways for improved governance and more sustainable outcomes. Travel and tourism comprise one of the largest economic sectors in the world. Despite the severe impacts of the coronavirus disease (COVID-19) pandemic on the sector (see subsect. 5B, chap. 7) from 2020 to 2022, travel and tourism contributed $10.15 trillion to global gross domestic product (GDP) (9.2%) and accounted for approximately 330 million jobs (10% of the global workforce) in 2023. Supported by strong tourism demand across regions, the global economic contribution of travel and tourism is estimated to have reached an all-time high of $11.1 trillion (10% of global GDP), supporting 348 million jobs in 2024 (World Travel and Tourism Council (WTTC), 2024a). In the future, the travel and tourism sector is expected to grow faster than other sectors of the global economy, contributing $16 trillion to global GDP (11.4%) and accounting for 450 million jobs (12.2% of the global workforce) by 2034.

As made clear in prior World Ocean Assessments, identifying the contribution of coastal and ocean tourism to the overall size of global tourism is challenging. Recent estimates by Northrop and others (2022) suggest that coastal and ocean tourism comprises at least 50% of all tourism spending, thereby accounting for more than $5.5 trillion (5% of global GDP) and employing roughly 174 million people. Importantly, coastal and ocean tourism is growing at a faster rate than international tourism as a whole and is expected to surpass offshore oil and gas as the largest sector of the ocean economy by 2030 (Organisation for Economic Co-operation and Development (OECD), 2016). In small island, archipelagic and coastal States, coastal tourism is often the predominant form of tourism and has a pronounced impact on economic activity (Pratt, 2015; McElroy, 2003).

As shown in the figure, the Caribbean remains the most tourism-dependent region in the world. In 2019, tourism accounted for approximately 14% of the region's GDP, 16% of employment and more than 20% of export earnings (WTTC, 2024a). Tourism's share of employment in the Caribbean is forecast to increase over the next decade to 18%, supporting nearly 1 in 5 jobs in the region. The Asia-Pacific region is also heavily dependent on tourism; the industry accounted for 11.2% of GDP and 12.5% of employment in the region in 2024.

Figure
Total contribution of travel and tourism to GDP



Source: Prepared by the writing team.

The WTTC forecasts that, by 2034, the travel and tourism sector will have grown by 3.7% per year, outpacing the expected 2.4% annual growth in the broader global economy, and contributing $16 trillion (11.4%) to global GDP, 101 million new jobs and employment for 449 million people (roughly 12.2% of the global workforce). Between 2024 and 2034, the Asia-Pacific region is expected to experience the fastest growth in travel and tourism (6.1%), with China projected to surpass the United States of America with the largest absolute contribution of tourism to GDP (WTTC, 2024a). Significant gains are also expected in India and Saudi Arabia.

Given its cross-cutting nature, importance to economic activity and human well-being, and critical dependence on environmental and cultural assets, tourism is uniquely positioned to contribute to all sustainable development pillars. However, when not properly managed, tourism can damage and degrade natural systems, deplete local resources and dilute culture, potentially diminishing destination appeal and offsetting economic gains from visitor spending. Strains on natural and cultural capital imposed by tourism can exacerbate vulnerability to climate change and economic shocks, leaving coastal communities increasingly at risk.

To balance the often competing needs of economic, environmental and community health and well-being (see subsect. 5B, chap. 3), it is necessary not only to make

investments that target market-based economic returns from tourism, but also to invest in the protection of natural and cultural amenities and heritage and equitable outcomes for local people. Contrary to the current trend towards mass tourism, evidence suggests that marine ecotourists spend more time and money at destinations than traditional tourists (Ressurreição and others, 2022; Topelko and Dearden, 2005).

Justifying public investment in natural and cultural capital is inherently challenging. While the economic value of tourism is relatively easy for policymakers to observe and appreciate in terms of arrivals and employment, the value to tourism of healthy coastal and marine environments and culture, and the economic costs that tourism creates remain largely hidden and underappreciated due to their indirect, non-market nature. The future sustainability of coastal and marine tourism will depend on closing the gap between science and policy through targeted use of data and analytics to understand the links between tourism, the environment and human well-being and communicating those connections to decision makers, investors, travellers and coastal communities. The links between tourism, coastal and ocean resources and socio-economic outcomes are outlined below and information is provided about alternative avenues for targeted investments to promote a more sustainable tourism sector.

2. Pressures and impacts

Coastal and ocean tourism is highly dependent on the health of natural resources, including beaches (see sect. 4, subchap. 5A), reefs (see sect. 4, subchap. 5D), mangroves (see sect. 4, subchap. 5H), marshes (see sect. 4, subchap. 5I), seagrasses (see sect. 4, subchap. 5G), seawater and numerous forms of wildlife, including birds (see sect. 4, subchap. 4G), fish (see sect. 4, subchap. 4D), sea turtles, pinnipeds and cetaceans. The health of these assets and their ability to attract visitors and contribute to economic activity and human well-being (see subsect. 5B, chap. 3) are under threat from an array of local and global pressures and impacts (Mafruhah, Supriyadi and Rahman, 2020; Mehvar, Khosravi and Zare, 2018; Mejjad and others, 2022).

Coastal tourism infrastructure, shoreline maintenance and protection

As pointed out in the first and second World Ocean Assessments, the increasing use of the coastal zone for leisure has transformed many of the world's coastlines (see subsect. 5A, chap. 9), making them more accessible for tourism and recreation, but also reducing their aesthetic appeal and the quantity and quality of ecosystem services that are vital to economic value and human well-being (see subsect. 5B, chap. 3). Compounded by sea-level rise (see sect. 4, chap. 3), many coastlines are receding (see sect. 4, chap. 6, and subsect. 5B, chap. 4) (de Schipper and others, 2021). To counter the loss of beaches and protect coastal real estate, many destinations have engaged in active shoreline maintenance and protection, including beach nourishment through sand replacement or the installation of shoreline armouring structures (see sect. 4, chap. 6) such as jetties, seawalls and groynes (Griggs, 2024; Hill, 2015; de Schipper and others, 2021). These changes can affect water flow, diminish water quality and cause the loss of valuable ecosystem services (Cooper, O'Connor and McIvor, 2020; Henderson and others, 2020; Liu and others, 2023). In addition, coastal tourism development can create issues of environmental justice when privatization of coastal lands, crowding and physical impediments imposed by built structures inhibit residents' access to and enjoyment of the coastline.

Solid waste

Tourism can generate large volumes of solid waste from lodging and leisure activities (Yusoff and others, 2022). Coastal tourism is the main source of plastic litter (see sect. 4, chap. 6) on beaches (Garcés-Ordóñez and others, 2020; Khadanga and others, 2022), the most common being food packages from beachgoers (Lamb and others, 2018). Solid waste management poses a challenge to small island destinations with tourism-based economies that have poorly developed waste infrastructure, have limited land area and are geographically isolated (Almroth and Kershaw, 2024). Islands are heavily dependent on imported goods but have little control over imported waste by-products. In addition, many must accept solid waste from cruise ships. This can lead to waste production exceeding management capacity, leaving few options other than landfills and incineration (Wang, Lee and Mokhtar, 2021). Poor solid waste management can have a negative effect on destination image and tourists' choices (Chaudhry and Sachdeva, 2021; Koliotasi and others, 2023).

Sewage and water pollution

Urbanization caused by tourism leads to water pollution (see sect. 4, chap. 6) through sewage or septic effluent and nonpoint source pollution from rain, storm water or snowmelt run-off. Polluted water that enters the ocean adds nutrients and induces excessive plant and algae growth, which can lead to hypoxia or "dead zones" in the water. Some algae are known to produce harmful toxins, which can create negative impacts on tourism visitation in coastal destinations (Berdalet and others, 2022; Yan and others, 2022; Nilsson and Gössling, 2013). In Florida, United States, for example, a bloom of the dinoflagellate *Karenia brevis* in 2018 caused $2.7 billion in economic losses to tourism-related businesses (Alvarez and others, 2024). Discharge of sewage and run-off also reduces seawater quality, leaving local and visitor populations vulnerable to illness (Rangel-Buitrago, Galgani and Neal, 2024).

Greenhouse gas emissions

The energy produced to meet the demands of coastal and ocean tourism generated an estimated 1.57 billion tons of carbon dioxide equivalent (CO_2e) emissions in 2023, representing 3% of global greenhouse gas emissions. Of these estimated 1.57 billion tons, 50% stems from supply chain sources (referred to as scope 3 emissions), 25% from direct emissions from sources owned or controlled by an organization, such as domestic transport (referred to as scope 1 emissions), 7% from indirect emissions from purchased energy (scope 2 emissions) and 19% from international transport (WTTC, 2024b). In many industrialized nations, the climate impact from long-distance travel (one-way trips exceeding 100 km) is greater than that from short-distance travel. Aviation is the major emitter in this sector, generating 2.4% of global anthropogenic CO_2 emissions in 2017 (Åkerman and others, 2021). Cruises are a particularly carbon-intense type of travel. While two of the major cruise liners report 2% annual improvements in carbon intensity in recent years and aim to continue improving at that rate (Royal Caribbean Group, 2021; Carnival plc, 2022), these figures refer to scope 1 and 2 emissions only, and a 2% reduction in carbon intensity is likely to be cancelled out by the expected 6–7% passenger growth (Hoegh-Guldberg and others, 2023).

Interactions with wildlife

Opportunities for wildlife-based recreation can yield significant benefits to tourists and local communities. For example, ecotourism based on marine megafauna is one of the fastest-growing sectors of ecotourism (Guidino and others, 2020). In Semporna, Malaysia, shark-diving tourism provided more than $9.8 million in direct expenditures per year (Vianna and others, 2018). Shark and ray tourism in Indonesia produces an estimated $22 million in direct expenditures annually, equivalent to at least 7% of the $1 billion in revenue from marine tourism in the country (Mustika, Ichsan and Booth, 2020). Recent evidence suggests that the popularity of shark diving could double in the next 20 years (Cisneros-Montemayor and others, 2020). However, interactions between tourists and wildlife, including noise and physical disturbance caused by human visitors, can affect the behaviour and fitness of animals by causing changes in foraging, migration and aggregation patterns, and displacement from preferred habitat, negatively affecting wildlife populations (Niella and others, 2023; Cattano and others, 2021; Shamir and others, 2019; Pavez and others, 2015). Populations that are spatially constrained or food-limited are most sensitive to tourism pressures and impacts (New, Lusseau and Harcourt, 2020). Beyond recreation, tourism can be an important driver of food systems and can lead to an increased demand for seafood (see subsect. 5A, subchaps. 1E and 1F), which has been associated with increases in fishing effort and unsustainable harvest practices (Miller, 2022). Touristic vessels are also a known pathway for the introduction of non-native species (see sect. 4, chap. 6) into marine environments and may have a disproportionate effect on the risk of introduction into marine protected areas (MPAs) (Parretti and others, 2020; Slišković and others, 2021). As highlighted in the second *World Ocean Assessment*, Antarctic and Arctic tourism have been growing rapidly in recent years. Coupled with heightened pressures on native biodiversity caused by the increasing pace of environmental change in polar regions, the seasonal timing of human presence in these regions increases the chances of direct human-wildlife conflicts, adverse impacts on endemic fauna and flora and the establishment of non-native species (see sect. 4, chap. 6) (Tejedo and others, 2022).

Mass tourism

The arrival of large amounts of visitors, although a means of economic activity and diversification, can negatively reshape local economies by increasing the cost of property and the overall cost of living (Garza and Ovalle, 2019), potentially leading to crowding out of locals (Zanini, 2017). Such trends can also hasten change in the skills necessary to prosper, which can be to the detriment of the resident workforce and may impact

equitable access to essential services (Albalate and Bel, 2010; Milano, Novelli and Cheer, 2019). Tourism's rapid recovery from the COVID-19 pandemic (see subsect. 5B, chap. 7) exacerbated problems associated with tourist volume and overtourism. Following the pandemic, there was a marked increase in tensions between tourists and residents and in pushback by locals on the impacts of overtourism on housing prices and availability, public services and degradation of natural areas and cultural sites (Amrhein and Langer, 2025; Milano, Novelli and Russo, 2024; Stojčić, Vizek and Glaurdić, 2024; González-Reverté and Guix, 2024). Protests calling for limits on tourism were held in popular coastal destinations in Greece, Italy and Spain and several locations in the United States, including New York, San Francisco, Los Angeles and Oahu. Several coastal destinations in Europe and Asia have imposed bans or restrictions on short-term rental platforms to mitigate tourism impacts on housing prices and availability (Wessel, Schmidt-Kessen and Hukal, 2024). Destinations in China, France, Italy, Spain and the United States have implemented economic incentive policies such as tourist fees to quell crowds (Choi, Jeon and Asperin, 2024). More radical proposals include complete or partial bans on cruise ships in port destinations such as Amsterdam in the Kingdom of the Netherlands, Barcelona in Spain, Dubrovnik in Croatia, Mykonos and Santorini in Greece, and Venice in Italy to offset the negative impacts of tourist crowding (Nepal and Nepal, 2021).

As the top destination for coastal and ocean tourism for millions of tourists, islands are particularly vulnerable to the impacts of mass tourism but are also dependent on visitor spending (Lagarias, Stratigea and Theodora, 2023; Butler and Dodds, 2022). However, the cost of managing tourism frequently outpaces the revenue generated and retained. Small islands often accumulate public debt as tourist arrivals rise (Peterson, 2023; Peterson and DiPietro, 2021). In Maldives, for example, tourism grew to represent 80% of the economy, while public account balances fell, leaving the nation in debt. Such "operational externalities" generated by costs on public infrastructure can leave nations with insufficient financing to manage tourism impacts (Epler Wood, Milstein and Ahamed-Broadhurst, 2019). An example of the scale of tourism that many small island developing States face is the Caribbean island of Aruba, which has a population of 105,000 and a land area of around 178 square kilometres, yet hosted over 1 million tourists in 2017 (Hampton and Jeyacheya, 2020).

Cruise tourism

Despite comprising less than 3% of all travel, the cruise industry is one of the fastest-growing sectors of tourism, with approximately 40 million passengers expected by 2027, supported by a fleet of over 330 cruise ships (Cruise Lines International Association (CLIA), 2024). It is one of the most common forms of mass tourism and is the dominant form of tourism in many coastal and ocean destinations (Bresson and Logossah, 2011; Domènech, Gutiérrez and Anton Clavé, 2020). North America and Europe remain the largest source markets for cruises, accounting for 57% and 26% of passenger volume, respectively, with the Caribbean and Mediterranean the most popular cruise destinations, receiving roughly 44% and 19% of travellers, respectively. For some island destinations in the Caribbean, the annual number of cruise passengers far exceeds the local population (World Tourism Organization, 2023). Although the impacts of cruise passenger spending are the subject of debate due to the short length of stay, limited spatial movement of passengers on shore (Spalding and others, 2023) and availability of on-board services and amenities (Gouveia and Eusébio, 2019), cruise ship arrivals can generate positive economic impacts for coastal communities (Chen and others, 2019; Artal-Tur, Navarro-Azorín and Ramos-Parreño, 2021). Large volumes of temporary visitors also create pressures on local water, food and waste disposal resources and produce large volumes of emissions, solid waste, sewage, greywater and oily bilge water (Lloret and others, 2021). The cruise industry releases 300,000 gallons of sewage, 8 tons of solid waste and 25,000 gallons of bilge water weekly, along with other by-products, at destinations and into national waters, causing a multitude of stress on marine ecosystems (Epler Wood, 2017; Kotrikla, Zavantias and Kaloupi, 2021; Lloret and others, 2021). Despite comprising less than 1% of the merchant fleet (CLIA, 2024), cruise ships release up to 25% of all fleet waste (Butt, 2007). Other impacts from cruise tourism include modification of nearshore ecosystems to accommodate cruise ships (Lester and others, 2016), damage from anchoring (Forrester and others, 2015; Rogers and Garrison, 2001; Small and Oxenford, 2022) and breakdown of the sociocultural make-up of destinations (Hoarau-Heemstra and others, 2023).

Recent estimates of carbon intensity based on annual reports from the three largest cruise lines (Carnival, Royal Caribbean and Norwegian) (Hoegh-Guldberg and others,

2023) suggest that the global cruise sector emitted approximately 60 Mt CO_2e in 2018, which is comparable to the annual emissions of many countries. With expected growth of 6% per year, emissions of 40 Mt CO_2e (scope 1 and 2 emissions) or 80 Mt CO_2e (scope 1, 2 and 3 emissions) are expected by 2030, trends that stand in stark contrast to global ambitions to halve emissions by 2030 (Hoegh-Guldberg and others, 2023).

3. Social components

The social and cultural sustainability of coastal and ocean tourism is also of considerable importance (Leposa, 2020). Opportunities for recreation and access to blue spaces drive travel to coastal and ocean locations and contribute to visitors' mental health, physical activity, enhanced psychological connection to the natural world (see subsect. 5B, chap. 2) and pro-environmental behaviours (Gascon and others, 2017; White and others, 2020). Evidence suggests that sustainable tourism initiatives can also generate significant social capital for coastal populations through economic diversification, cultural and natural heritage preservation and educational infrastructure development (Papageorgiou, 2016; Bennett and others, 2017). Tourism revenues can be harnessed as a means of boosting employment and addressing core issues relating to poverty (Zhang, Wang and Yang, 2023). Marine ecotourism can also empower community members to serve as environmental stewards, finance and expand MPAs and promote ocean literacy and citizen science (Bushell and Bricker, 2017; Cusack and others, 2021; Morse and others, 2024; Ressurreição and Giacomello, 2013). It can also facilitate the transmission of traditional ecological knowledge, thereby reinforcing place-based cultural identities (Pomeroy and others, 2007).

However, there are sociocultural challenges associated with ocean tourism development, particularly regarding power asymmetries between external stakeholders and local populations, and adverse effects on residents' well-being from the pressures and impacts outlined above. The phenomenon of cultural commodification is a documented concern, wherein culturally significant marine practices undergo transformation into commercialized experiences for tourist consumption (Mostafanezhad and Norum, 2019). Other adverse socioeconomic impacts from tourism such as congestion, higher prices, seasonal unemployment, economic leakage, distributional inequality and dilution of culture can induce negative host attitudes towards tourism and restrain the sustainable development of the sector (Canavan, 2016; Fan, Liu and Qiu, 2019; Frent, 2016). Dissimilarities between the social and cultural norms of visitors and host communities can also create tensions, resentment, irritation and conflict (Lehto, Davari and Park, 2020). This will be evidenced in the coming years with the entry into coastal tourism development of countries like Saudi Arabia. Returns from their recent and significant investments in tourism may hinge on accommodating visitors in a culturally sensitive manner and blending tourism development with the sociocultural norms that reflect the country's religious heritage (Ghaderi and others, 2024; Zamani-Farahani and Henderson, 2010).

4. Sector-relevant governance

The tourism industry is highly fragmented, comprising a variety of product and service markets, including transportation, accommodation, attractions, nightlife, recreation and food and beverages, and is intrinsically connected to other economic sectors and the broader macroeconomy. Coastal and ocean tourism involves public and private goods, asymmetric power across stakeholder groups and a coupling of dependence and impact between the economy and the natural environment.

Owing to these challenges and complexities in governance, progress towards sustainable coastal and ocean tourism requires policy coherence across numerous private and civil society stakeholders operating at the local, national, regional and international levels, and clear and accurate understanding of the magnitude and direction of change (Leotaud and others, 2024; Dwyer, 2003). Increased interest in new forms of governance for sustainable tourism has been driven in recent years by heightened sustainability awareness, smarter tourism development and management for both tourists and residents, a rising call for social inclusion, new technologies, a growing need for resilience and increasing governmental interest in destination governance and stewardship (Imbsen and others, 2021; Reinhold and others, 2023).

Prerequisites include a unified vision and organization at the destination, national and regional levels, the effective use of data and information, and clear communication and cooperation across a range of stakeholder groups (Scott, 2013).

Current research advocates for governance frameworks characterized by collaborative decision-making mechanisms that allocate substantive authority to local actors regarding marine tourism development trajectories (Milne and Ateljevic, 2001; Kelly and others, 2018). Such community-forward frameworks necessarily encompass equitable labour standards, support for local enterprise development, and protocols for cultural exchange predicated on community-determined parameters (Asker and others, 2010; Jackson, 2025). There is also an imperative to integrate Indigenous knowledge systems as foundational elements within sustainable tourism paradigms rather than as peripheral considerations (Nursey-Bray and Rist, 2009). Engaging local communities in the visioning, planning and co-management of sustainable tourism initiatives can generate and renew knowledge, awareness and pride in local ecosystems, history and traditions, foster local ownership, stimulate interest and investment in preservation and ensure that tourism practices align with ecological and cultural values (Bichler, 2021; Kuba, Kuba and Sani, 2024; United Nations Educational, Scientific and Cultural Organization (UNESCO), 2021).

The integration of environmental, social and governance principles into tourism business models has increased in recent years in response to consumer and investor pressure to engage in responsible practices and to build organizational resilience against environmental and social risks in an increasingly volatile global context (Gössling, Scott and Hall, 2020). Environmental, social and governance practices can improve operational efficiency related to environmental impacts associated with agriculture, water and waste management systems, while enhancing community engagement and advancing the fair treatment of employees (Back, 2024). While research into the impact of corporate environmental, social and governance strategies on financial returns is limited, preliminary evidence suggests that engaging in corporate social responsibility activities can yield positive returns for tourism and hospitality firms in terms of performance and market value and that factors related to governance and stakeholder engagement are critical components of success (Ionescu and others, 2019; Legendre, Ding and Back, 2024).

At the destination level, the creation of a central tourism management organization taking into consideration private and public sector tourism interests and involving community leaders can be effective in coordinating goals across the complex and multi-stakeholder nature of the sector and ensuring open and inclusive participation (Bichler and Lösch, 2019; Waligo, Clarke and Hawkins, 2013). To assist destinations in advancing inclusive destination governance, the WTTC has not only a destination stewardship governance diagnostic framework that provides alternative destination stewardship scenarios, but also a diagnostic tool to identify triggers and barriers to effective destination stewardship, assess different aspects of destination governance and identify priority areas for improvement (WTTC, 2021).

Modes of regional governance can provide many benefits to coastal and ocean tourism destinations, including opportunities for capacity-building, improved access to data and resources, risk-sharing and efficiency gains from economies of scale (Tausch, 2016). Establishing regional coordination through governance mechanisms can also help to minimize price competition between locations, which can induce a "race to the bottom" in terms of sustainability (Dwyer, 2003; Grydehøj and Kelman, 2017). International cooperation and collaboration can be enhanced through the formation of regional clubs designed to promote shared values and understanding across diverse tourism actors and unite economic and social interests. Coordination of environmental policies between countries (e.g. standards for cruise ships, tourist fees earmarked for conservation, environmental tax rates) can address the concerns of domestic industries that may be vulnerable to international competition (Coste and others, 2018).

5. Sustainable pathways

The future of coastal and ocean tourism will be shaped by global economic conditions such as the availability of disposable income and leisure time, the costs of energy and travel, information technology, demographics and global environmental change. Ocean acidification and rising sea temperatures (see sect. 4, chap. 3) are expected

to have continued detrimental impacts on nearshore ecosystems (Guild and others, 2024; von Schuckmann, Minière and Cheng, 2024), affecting destination appeal and leaving coastal destinations increasingly vulnerable to the effects of a changing climate (Hoegh-Guldberg and others, 2007; Ward and others, 2016). Despite commitments by Member States at the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change and noticeable progress since the adoption of the Paris Agreement, a large climate action gap remains and appears unlikely to close soon (World Economic Forum, 2024), suggesting that coastal and ocean destinations should anticipate continued impacts from changes in temperature and rainfall, warmer seas, rising sea levels (Cazenave and Mitchum, 2024) and hazardous weather events (Catalano, Forni and Pezzolla, 2020).

Younger and wealthier travellers, a larger middle class, low transportation costs and increasing demand for experiential travel suggest that tourism volume will continue to grow and "overtourism" will continue, bringing continued pressures and tensions between visitors and local populations. As with all economic sectors, the tourism sector will be characterized by increasing access to richer and more comprehensive data, indicators and processing power, including machine learning and artificial intelligence tools, providing unprecedented opportunities for visitor engagement and improved understanding of tourist preferences, behaviours and impacts (Spalding and others, 2023).

Transitioning towards a more sustainable future will involve investments to mitigate dependence on tourism and build resilience to the pressures and impacts outlined above, while safeguarding the economic viability of the sector by restoring and regenerating the natural and cultural capital that attracts visitors and supports local communities (Gounder and Cox, 2022; Northrop and others, 2022; Richardson and Witkowski, 2010). Given the diverse array of coastal and ocean destinations across the globe and the complex and highly contextual relationships between tourism and economic, environmental, social and cultural outcomes, there is no one-size-fits-all prescription for the future of the sector (Brida, Gómez and Segarra, 2020; Nunkoo and others, 2020).

Four complementary pathways for reorienting coastal and ocean tourism towards more sustainable outcomes are set out below. These pathways assume that other ocean sectors (e.g. capture fisheries (see subsect. 5A, subchaps. 1A and 1B), shipping (see subsect. 5A, chap. 6) and extraction of energy resources (see subsect. 5A, subchap. 3B)) will continue and that unfettered market forces will not provide efficient investment in protection and regeneration of ecosystems and cultural resources (Schuhmann, 2020).

Each pathway addresses the array of environmental and social impacts created by tourism outlined above and relies on purposeful planning and investment. A key challenge in achieving investments in environmental and social capital is that the associated returns are often not observable in terms of traditional economic indicators and may only be apparent over a time frame that is longer than election cycles. Most nations have limited fiscal space for long-term investments with unclear returns. Key elements of sustainable pathways across destinations therefore include improved access to financial resources to support investment in natural and social capital, enhanced data collection and analysis to illustrate economic returns from that investment and the creation of inclusive governance frameworks to support policy and legislation that incentivize information-sharing and private sector investment in sustainable outcomes (World Economic Forum, 2024).

Investment in data collection, publication and analysis to understand linkages between tourism and natural and cultural resources and the full costs and benefits of tourism

Many of the amenities that attract visitors to coastal and marine destinations are open-access public goods, generating no direct economic impacts, but serving as key drivers for market-based activities that generate income and employment (National Oceanic and Atmospheric Administration, 2023). A deep body of research illustrates that maintaining or enhancing the quality of coastal and ocean ecosystems allows for significant contributions to economic growth, employment and poverty reduction while enhancing resilience to climate change, natural disasters and economic shocks (Patil and others, 2016). Damage to coastal and ocean systems entails real economic costs. Eroded or littered beaches (see sect. 4, subchap. 5A and chap. 6), degraded reefs (see sect. 4, subchap. 5D) and polluted seawater (see sect. 4, chap. 6) are known to be less attractive to tourists (Qiang, Shen and Xie, 2020; Schuhmann and others, 2016) and loss of coastal ecosystems puts tourism assets at risk (Barbier, 2015; Spalding and others, 2014).

Despite these well-known findings, coastal and marine ecosystems continue to be modified, damaged and degraded by human activities associated with market-based returns (Atwood and others, 2017; Riegl and others, 2009). Part of this dichotomy lies in the fact that market-based metrics such as arrivals, spending, jobs and revenues are widely publicized and easily understood, while measures of ecosystem health and function lack clear and appropriate monetary signals, creating a situation where private and public interests are naturally inclined to prioritize market values. This information gap inhibits sustainable management, as policymakers must operate with incomplete understanding of connections between traditional economic activity and natural and cultural capital (Thorburn, Milne and Deuchar, 2021).

Measuring the impacts of tourism on natural and cultural resources is an integral part of monitoring and controlling those impacts (Papathanassis, 2023). Investments in the comprehensive collection and analysis of economic, social and environmental data can facilitate empirical assessments of the relationships between market activity and environmental and cultural sources of human well-being (see subsect. 5B, chap. 3), such as ecosystem health and extent, maintenance of local knowledge and traditions, and equitable distribution of the economic benefits from tourism. Avenues for data collection to support the enhanced monitoring, assessment and prediction of ecosystem health include advanced mooring systems that facilitate the collection of real-time data on seawater quality, biodiversity, climate variability and ocean hazards. Smart tourism apps can help to measure and manage ecological footprints and carrying capacities, assess visitor satisfaction, enhance operational efficiency and reduce waste (Pencarelli, 2020; Wang and others, 2016; Yu, Zhang and Wang, 2018). Smart technology can also facilitate the bidirectional exchange of information with visitors, further engaging them in destination sustainability by guiding and informing decisions regarding purchases, experiences and movement. An example of the power of digital tools and improved access to data is the use of mandatory global navigation satellite system trackers to monitor local seafood in the tourism sector in Jamaica, where consumers are increasingly demanding supply chain transparency and traceability (Northrop and others, 2023). Digital data-gathering mechanisms like apps empower local fishers (see subsect. 5A, subchap. 1B) while giving consumers confidence in premium-priced, sustainably labelled seafood (see subsect. 5A, subchap. 1E).

Coupling traditional measures of economic impacts from tourism with measures of non-market impacts, such as waste generation, water and energy use, crowding, ecosystem health and qualitative forms of information such as visitor and resident satisfaction, can form the foundation for education and capacity-building programmes designed to help policymakers, tourism operators and civil society to understand the real economic value of natural and cultural resources and redefine the notion of tourism success (Frantzeskaki and others, 2019; Schuhmann, 2020). Beyond the provision of a clearer view of tourism's impacts on ecosystems and communities, the measurement and mapping of ecosystem service stocks, flows and values can support evidence-based decision-making (Schumacher and others, 2020; Spalding, Burke and Fyall, 2021) for investment planning and for designing policies that direct resources towards their highest and best use (Papageorgiou, 2016; Schuhmann, 2020). Empirical evidence regarding the economic losses created by tourism can also help destinations to negotiate and implement tourist fees (e.g. cruise passenger fees) commensurate with costs imposed on local resources and infrastructure.

Echoing the recommendations of the Ocean Decade Vision 2030 (Calewaert and others, 2024) and the Intergovernmental Oceanographic Commission (IOC-UNESCO) *State of the Ocean Report 2024* (O'Brien and others, 2024), this pathway may require increased investment in data literacy, information technology readiness, the updating and modernization of national statistical offices and systems, data collection and data-sharing, and analysis efforts that span disciplinary and geographical boundaries. Natural capital accounting methods, such as the System of Environmental-Economic Accounting and ocean accounts,[1] provide structure for such data using a framework that is compatible with traditional national income accounts used by statistical offices and finance ministries. Creating and maintaining such accounts

[1] Ocean accounts are integrated, standardized records that provide a comprehensive view of a country's environmental conditions, economic activities and social conditions related to ocean resources. Ocean accounts facilitate tracking of economic progress, allowing countries to go "beyond GDP", measuring not just market output but also the value of ecosystem services, the condition of natural assets and the impact of human activities on the ocean environment. For more information, see www.oceanaccounts.org.

can foster and improve collaboration and coordination across government entities, help to identify gaps and deficiencies in data and statistics related to national priority issues (e.g. energy efficiency, water use, emissions and protected area management), help to measure and manage risks and opportunities related to nature, and improve stakeholder engagement (Fenichel and others, 2023; Ingram and others, 2024; King and others, 2024; Perkiss and others, 2022). By mapping tourism's linkages with coastal and marine ecosystems, ocean accounts also demonstrate the sector's vested interest in supporting ocean conservation, safeguarding its own future prosperity, and can be used to identify sustainable scenarios and pathways (Gacutan and others, 2022).

High-quality, immersive nature-positive and authentic community-based tourism

A broad body of empirical evidence shows that immersion in nature and culture can stimulate place attachment, sustainable behaviours and willingness to return (Chen and Rahman, 2018; Kil and others, 2012; Wilkins and de Urioste-Stone, 2018; Zhang and others, 2023) and that tourists are willing and able to give back (Adam, 2021; Wearing and McGehee, 2013). Developing and promoting opportunities for high-quality, immersive nature-positive and authentic community-based tourism experiences can foster connections between visitors and marine environments, attract longer-staying visitors who spend within the local economy, strengthen visitor awareness of local conservation issues and enhance resiliency by counteracting tourism seasonality, while creating opportunities for employment, entrepreneurship and economic empowerment (Leotaud and others, 2024; Lewis-Cameron and Brown-Williams, 2022; Vergori and Arima, 2020). Well-designed experiences can cultivate visitors' ocean literacy and environmental consciousness that extend beyond the travel period (Ballantyne and others, 2018), generating ripple effects as tourists return home with new perspectives on ocean conservation, potentially influencing consumption patterns and political support for marine protection (Zeppel and Muloin, 2008; Walker and Moscardo, 2014). For coastal communities facing climate threats, sustainable tourism initiatives can serve as a vehicle for climate adaptation education, helping both residents and visitors to understand changing ocean conditions while building collective resilience against environmental uncertainties (Sheller, 2021; Cinner and others, 2018).

Examples of nature-positive community-based opportunities include the sustainable community tourism initiative in the Dominican Republic, which links communities with tourists emphasizing proper management of natural resources, appreciation of cultural heritage, equitable distribution of benefits from tourism and local community development through empowerment, entrepreneurship and self-management.[2] Tourist scuba divers in Fiji can join with local non-profit organizations and engage in citizen science or participate in more active pursuits such as coral restoration, creating a triple win: improved data and knowledge, action that advances conservation, and enhanced tourist satisfaction and willingness to return.[3] Blue Safari Seychelles is a company that allows visitors to help to protect marine ecosystems through data collection of encounters with species, tree planting, beach clean-ups and underwater debris collection.[4] Travellers pay a daily conservation charge of $25, earmarked for ecological programmes and initiatives (Thorburn, Milne and Deuchar, 2021). Other examples are shown in the table.

Opportunities to inform visitors regarding the importance of environmental and cultural assets and the purpose of sustainability initiatives can further engage visitors and stimulate responsible behaviour (Aini and Syuraini, 2023; Downs, Cruz and Remengesau Jr., 2022; Leotaud and others, 2024). Codes of conduct, such as the Palau Pledge,[5] incentivize tourists to interact with the local community and culture and participate in regeneration projects (Herrmann, 2022; Levitan-Haffar, 2022). The Palau Pledge is stamped in all tourists' passports, which they must sign before passing through customs (Levitan-Haffar, 2022). An emerging area is improving access to information regarding the environmental impacts of trip decisions and enabling tourists to make carbon-offset contributions to blue carbon investments such as mangrove restoration or choose lower-emitting flights and accommodation using carbon calculators and carbon data transparency initiatives, such as Skyscanner and Google.

2 See www.godominicanrepublic.com.
3 See www.fijimarinas.com/citizen-science.
4 See https://bluesafari.com.
5 See https://palaupledge.com.

Challenges to implementing nature-positive and community-based tourism include: scaling due to reliance on small enterprises and carrying capacities of sensitive cultural sites and ecosystems; maintenance of natural and cultural integrity; and avoiding the commodification of culture and heritage. To ensure long-term success and community buy-in, it is essential for residents to be fully engaged in the co-development of such initiatives. Inclusive capacity-building and training in sustainable practices targeting local management and/or ownership of commercial tourist enterprises can further empower residents.

Table
Nature-positive and community-based tourism initiatives

Active	
Preservation	Shoreline and marine clean-up efforts; invasive species removal
Regeneration	Mangrove planting; seagrass propagation; coral restoration; tree planting; dune restoration; marsh restoration; restoration of tidal flows and natural hydrology
Citizen science	Encounters with species; species counts; water quality or clarity assessments; litter counts
Nature- and culture-based adventures	Wildlife and habitat viewing; fishing; diving and snorkelling; cooking and cuisine
Passive	
Tours and visits	Museums; coastal ecosystems; historic and heritage sites; visual and performing arts
Local goods and services	Markets for local arts and crafts, products and services; health and wellness
Non-intrusive access to nature	Boardwalks, bridges, wildlife viewing structures; species identification and other interpretive signage
Immersive learning experiences	Cultural interpretation of natural environments and species, storytelling, history and heritage; importance of ecosystems; endemic biodiversity

Source: Adapted from Thorburn, Milne and Deuchar, 2021; and Leotaud and others, 2024.

Multi-use planning and diversification for infrastructure, services and operators

This can provide backstop income and employment opportunities during periods of tourism disruption and enhance destination resilience to natural hazards and economic shocks. Public investments in infrastructure improvements targeting energy efficiency, maintenance of water and waste management infrastructure, and protection of ecosystems and biodiversity have been shown to provide positive economic and environmental returns (Paramati, Alam and Lau, 2018). Opportunities for tourism diversification include niche markets such as ecotourism, cultural and heritage tourism and community-based tourism (Leotaud and others, 2024). Increasing focus on service quality for business travellers and providing incentives to extend visits beyond the work period can offset losses from the decline in demand for business travel, generate additional economic impacts and create new opportunities for return visitation. Examples include remote work visa programmes that target digital nomads (Sánchez-Vergara, Orel and Capdevila, 2023). Investments in local capacity-building, such as training marine tourism operators to monitor protected sites and collect data regarding ecosystem health and function, can also enhance economic resilience to tourism downturns and empower tourism stakeholders as stewards of the natural environment (Day, 2008). A key challenge is that diversifying tourism value chains and decreasing economic dependence on tourism require structural reform.

Enhanced use of economic instruments to incentivize the transition towards sustainable outcomes and create fiscal space for investments in natural and cultural capital

Coastal and ocean tourist destinations can use an array of fiscal policy tools to harness the power of monetary incentives and direct financial resources towards activities that generate long-term economic returns through regeneration and resilience, pollution reduction and the increased sustainability of tourist attractions. Taxes,

fees, subsidies and payments for environmental services have been shown to be effective in funding protected area management, green energy, nature-based solutions, the decarbonization of supply chains, waste and emissions reductions and water use efficiency without constraining economic and social development or deterring visitation (Olmstead and Stavins, 2009; Sun and Feng, 2023; von Saltza and Kittinger, 2022).

Tourist fees can serve the dual purpose of revenue generation and visitor management. A large body of empirical evidence suggests that visitors are willing to pay fees that improve resource quality or offset management costs when the purpose is clearly communicated (Edwards, 2009; Font, Cochrane and Tapper, 2004; Rivera-Planter and Muñoz-Piña, 2005). In addition, collection points for visitor fees create a conduit for bidirectional exchange of information, enabling enhanced visitor management and the education of tourists on codes of conduct, the importance of natural systems, history, culture and traditions, and environmentally and culturally responsible behaviours, and facilitating the collection of information related to tourist activities, spending, preferences and satisfaction.

In addition, Governments can incentivize private sector sustainability initiatives through monetary and operational subsidies such as favourable tax treatment and fast-tracked permits for tourism projects that promote renewable energy, green products and services, locally sourced inputs, high-quality and low-volume experiences and community benefits (Leotaud and others, 2024; World Economic Forum, 2024). Special events, visitor concessions for off-season trips and visits to less popular sites and attractions can also be used for visitor management and for the reduction of the impacts of seasonality (Connell, Page and Meyer, 2015). Quota or reservation systems can also be used for high-demand or sensitive sites. Destinations must first measure and understand capacity limits in terms of adverse impacts on ecosystems, cultural integrity, water and energy resources, infrastructure, community well-being, safety and visitor satisfaction.

6. Conclusion

The review of the nature and extent of coastal and ocean tourism and its impacts on human and environmental well-being set out above highlights a coupling of dependence and impact. Economic and social gains from coastal and ocean tourism rely on the ability of coastal and marine ecosystems to provide benefits to visitors and local communities. However, mounting evidence suggests that continued growth of the sector poses threats to the natural and cultural resources upon which tourism depends.

Transitioning coastal and ocean tourism towards more sustainable outcomes will require a shift among tourism stakeholders to view the value and success of tourism more holistically, complementing traditional market-based measures of economic activity with measures of environmental, cultural and community costs and benefits. This shift will require purposeful public and private sector investments. Investments in data collection and analysis can close information gaps, allowing for a more comprehensive view of tourism's value and impacts, facilitating evidence-based planning and decision-making and providing the foundation for education and capacity-building programmes. Support for nature-positive and community-based tourism opportunities can create economic gains and empower both visitors and local communities to be agents of change. Multipurpose infrastructure and diversification of product and service offerings can improve economic efficiency and enhance destination resilience to natural hazards and economic shocks. Enhanced use of economic instruments can incentivize sustainable behaviours and create revenue streams to support investments in natural and cultural capital.

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Chapter 5
Use of genetic resources and biotechnology

Key points

- Marine genetic resources hold great potential but remain largely understudied, with most areas beyond national jurisdiction and the deep sea still unexplored. Even marine genetic resources from accessible and well-known marine environments (e.g. coastal areas) are still little investigated compared with genetic resources from terrestrial systems.
- Advancements in the marine genetic resources research and development pipeline have contributed to increasing interest in biodiscovery in marine environments, including the deep sea, particularly of marine microbes, including microbiomes. There are wide-ranging potential applications, including industrial processes, environmental mitigation and health, especially medicines.
- Marine genetic resources, and the fair and equitable sharing of the benefits thereof, are one of four main elements addressed under the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction. Engagement by the scientific community will be necessary to achieve objectives related to marine genetic resources in the Agreement, including advancing conservation and promoting marine scientific research, capacity-building and the transfer of technology.
- Coordination is needed on benefit-sharing relating to marine genetic resources and digital sequence information and the conservation of marine biodiversity within and beyond national jurisdictions across multilateral environmental agreements (the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction and the Convention on Biological Diversity and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization to the Convention on Biological Diversity).
- Equitable, interdisciplinary approaches to access to and use of marine genetic resources and biotechnology are central to addressing existing knowledge and capacity gaps, and also provide a basis for addressing global challenges of planetary and human health, thereby building sustainable and inclusive futures.

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1. Introduction

A remarkable diversity of life is found in the ocean, which is home to species from 33 of the 34 major animal phyla (Sigwart and others, 2021a). Living organisms have evolved in the ocean for 3 billion years longer than they have on land, with resulting deep evolutionary diversity, and have adapted to thrive in complex habitats, some of which are characterized by extreme temperature, salinity and the absence of light. Extreme conditions and habitat heterogeneity, such as hydrothermal vents and abyssal plains in the deep sea, also drive adaptation and evolutionary novelty (Le Bris and Gaill, 2007; Sun and others, 2020). The vast genomic diversity of marine ecosystems therefore offers a reservoir of genetic resources and biological innovations, with marine organisms producing a wide variety of specific and potent bioactive substances (Carroll and others, 2023; Cordier and others, 2022; Blasiak and others, 2021; Reverter and others, 2020; Arrieta and others, 2010).

In the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, marine genetic resources are defined as "any material of marine plant, animal, microbial or other origin containing functional units of heredity of actual or potential value". Marine genetic resources therefore encompass all forms of marine biodiversity and also provide raw materials for marine natural products, or bioactive chemical compounds produced by marine organisms. Marine biotechnology is the discovery and usage of marine genetic resources (and isolation of marine natural products) for a wide range of potential applications, including human and animal health, improvement of industrial processes, climate change mitigation, bioremediation and the management of invasive species, biomimetics, and areas where marine genetic resources can inspire novel materials and structural design innovations (Blasiak and others, 2020, 2022; Harden-Davies and others, 2020; Jaspars and others, 2016; see also sect. 3).

In recent decades, around 42,000 marine bioactive compounds have been extracted, identified and characterized (Carroll and others, 2023). Marine organisms demonstrate higher bioactivity than terrestrial ones in various studies (Francesch and others, 2024; Saravanan and Debnath, 2013; Appleby and others, 2016). While roughly 1 in 5,000 to 10,000 tested terrestrial compounds leads to applications, this rises to 1 in 2,550 for marine compounds, potentially due to high levels of bioactivity in some species (Royal Society, 2017; Gerwick and Moore, 2012). However, marine and terrestrial compounds appear to be more closely related than previously thought, suggesting that marine genetic resources research should be focused on the subset of unique natural product diversity in the marine realm (Voser and others, 2022). Many new discoveries are expected, including new species (metazoans or microbes), antimicrobial defences, mechanistic pathways, immune strategies and chemical compounds, all with potential applications in biotechnology.

This potential, however, has yet to be translated into a step change in research into marine genetic resources and marine biodiversity (Sigwart and others, 2021a), particularly in the deep sea and areas beyond national jurisdiction, where biodiversity has been little explored. In deep-sea regions of the Pacific, for example, an estimated 80% to 90% of species are new to science (Rabone and others, 2023; Kennedy and others, 2019). Only 0.001% of the deep sea has been visually observed (Bell and others, 2025). To date, marine biodiscovery has been focused on a relatively small group of organisms and habitat types (Francesch and others, 2024). Only 1,639 marine species have genetic sequences associated with patents (Zhivkoplias and others, 2024) of the approximately 250,000 currently known marine species in the World Register of Marine Species database (WoRMS, 2025),[1] with new species discovered at a rate of around 2,300 annually. Only a handful of medicines have been derived from marine genetic resources to date, with the 15 to 20 approved drugs derived from marine sources (Francesch and others, 2024; see also www.marinepharmacology.org/approved) representing a tiny fraction of the discovery potential.

[1] See www.marinespecies.org/.

2. Recent trends and developments since the second *World Ocean Assessment*

Ongoing developments in marine genetic resources research and development and biotechnology have contributed to increasing interest in marine biodiversity (Francesch and others, 2024; Zhivkoplias and others, 2024). The exploration of marine genetic resources has been facilitated in recent years by improved and lower-cost sequencing technologies and bioinformatics tools. Since the publication of the second *World Ocean Assessment*, sequencing techniques have been greatly advanced, including through in situ sequencing platforms, synthetic biology, environmental DNA/metabarcoding, and multiomic approaches utilizing genomic, metagenomic, transcriptomic, proteomic and metabolomic data in tandem (Francesch and others, 2024; Laiolo and others, 2024; Govindarajan and others, 2022; Reverter and others, 2020). Other key developments include the use of artificial intelligence and automation in sampling and collection and analysis (Rabone and others, 2025).

These rapidly developing techniques open up marine environments that have previously been challenging to sample and can facilitate conservation processes, environmental monitoring and biodiversity discovery efforts (Arnaud-Haond and others, 2020; Lewin and others, 2018), as well as establish baselines underpinning global commitments on biodiversity conservation. A total of 1,425 new bioactive compounds were reported from marine organisms in 2021 alone (Carroll and others, 2023). Increased patenting activity of products derived from marine genetic resources is also evident, with 4,779 patent filings referencing marine genes from 1,639 different marine species identified in 2024 (Zhivkoplias and others, 2024). There is an increasing focus on deep-sea species for biodiscovery (Zhivkoplias and others, 2024), likely driven by their high diversity and myriad adaptations to extreme conditions, combined with increasing accessibility. Marine microbes, including host-associated microbiomes of metazoans such as sponges, show great natural product potential (Carroll and others, 2023; Hesketh-Best and others, 2023; Williams, 2009; Bérdy, 2005), and new studies have revealed previously unreported levels of biodiversity and novel function of the global ocean microbiome (Chen and others, 2024; Vohsen and others, 2024; Schubotz and others, 2024). New techniques for rapid microbial biodiscovery are also emerging, including the use of in situ cultivation and metagenomics tools (Bogdanov and others, 2024). Developing applications include bioremediation by genetically modified bacteria (Sajjad and others, 2024).

Pharmaceutical development remains a central focus for research related to marine genetic resources and biotechnology efforts (Francesch and others, 2024; Papon and others, 2022; Lindequist, 2016). More broadly, marine genetic resources remain far less investigated and characterized than terrestrial counterparts (de Jong and others, 2024; Carroll and others, 2023; Voser and others, 2022), and marine biotechnology in some respects can still be considered an emerging or even nascent field (Daniotti and Re, 2021). Large-scale initiatives to map the ocean genome are under way, which are aimed at improving knowledge of marine species and providing libraries of reference genome data to support further research. These include the Earth BioGenome Project (Lewin and others, 2022), the Ocean Genome Atlas Project, the Aquatic Symbiosis Project (McKenna and others, 2024), ATLASea in French exclusive economic zones and the recently developed KAUST Metagenomic Analysis Platform (KMAP) Global Ocean Gene Catalog (Laiolo and others, 2024).

There are also recent developments in governance frameworks for marine genetic resources. The Convention on Biological Diversity and the Nagoya Protocol on Access and Benefit-sharing provide a framework for the fair and equitable sharing of benefits derived from genetic resources from areas within national jurisdiction. Recently, the Conference of the Parties to the Convention on Biological Diversity, in its decision 16/2, adopted modalities for operationalizing a new multilateral mechanism for benefit-sharing from the use of digital sequence information within national jurisdictions. The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, adopted in 2023 and entering into force in January 2026, provides a new legal framework for equitable access and benefit-sharing of marine genetic resources and associated digital sequence information from areas beyond national jurisdiction (de la Concepción, 2024; see also sect. 3 and subsect. 5B, chap. 5).

3. Pressures and impacts

Our global ocean is under the threat of unprecedented loss of biomass and biodiversity from multiple (and frequently cumulative) anthropogenic pressures, including climate change, pollution and the impact of overfishing and extractive industries (Crona and others, 2021; Vieira and others, 2023). Rapidly changing environmental conditions due to these anthropogenic stressors have resulted in widespread marine ecosystem degradation and biodiversity loss, with impacts evident from coastal habitats to the deep sea and from polar habitats to the equator. In coastal regions, fisheries, aquaculture and coastal development have directly affected habitats, affecting genetic diversity and the populations of certain species, particularly in tropical areas rich in biodiversity such as mangrove forests, coral reefs and seagrass habitats (International Union for Conservation of Nature (IUCN), 2024; Herrera and others, 2022; Morrison and Aalbersberg, 2022; Salimi and others, 2021; Thomas and others, 2017). Climate change has affected the diversity and distribution of marine species through processes of ocean warming, acidification and deoxygenation (Levin, 2018; see also sect. 4, chap. 3). In addition to the manifold negative impacts for humanity from affected ecosystems, countless species and potentially invaluable marine genetic resources (including those that could help to address challenges in planetary and human health) may be lost before they are even discovered. Addressing ocean health is therefore doubly crucial for the conservation of marine biodiversity and marine genetic resources and provides the backdrop for marine biodiscovery and biotechnology activities (see subsect. 5B).

4. Sustainability pathways

Maintaining a balance between the resilience of marine ecosystems and their utilization will require coordination of research, governance and economic activities (including responsible management of global supply chains) (Kittinger and others, 2024). This can be aided by global efforts to address biodiversity knowledge gaps (Laiolo and others, 2024; Rabone and others, 2023; Rogers and others, 2023), the application of genetic/genomic monitoring tools, cooperative interdisciplinary marine scientific/biodiscovery research (Zhivkoplias and others, 2025), holistic approaches to valuing marine genetic resources (Krusberg and others, 2024) and developing sustainability pathways and ocean futures (Pereira and others, 2023). Marine genetic resources and marine biotechnology have often been conceptualized as "future" or "emerging" elements of an ocean economy that generated over $1.9 trillion in revenues in 2019 alone (Claudet and others, 2021; Virdin and others, 2021, World Wildlife Fund (WWF), 2025). It is timely, therefore, to develop pathways for equitable and sustainable use of marine genetic resources (Krusberg and others, 2024). The present part of the chapter introduces aspirational pathways in the lead-up to 2050, envisaging an ideal future in which marine genetic resources are accessed and used in a fair and inclusive manner, contributing a broad range of monetary and non-monetary benefits and improved conservation outcomes (Claudet and others, 2021; Martin and others, 2022). Proceeding along this pathway will require coordinated steps across several disciplines (Crona and others, 2021), as outlined below.

Governance

In our scenario, after the entry into force of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, a clearing house mechanism and subsidiary bodies will be rapidly established that are tasked with achieving consensus on modalities and levels of benefit-sharing for marine genetic resources. By 2030, the legal clarity provided by the Agreement and its clearing house mechanism will have facilitated a new era of exploration and marine biodiscovery in the deep sea. To ensure fair and equitable access to marine genetic resources, including their utilization for marine conservation, a network of regional centres of excellence will be established, catalysing knowledge exchange. Alongside legally binding regulations, new norms of inclusivity will become increasingly embedded throughout marine scientific endeavours, with each research project (and resulting expedition) composed of scientists from diverse backgrounds (de Vos and others, 2023; Wang and others, 2024; Amon and others, 2022; St Clair, 2021). An extensive library of publicly available novel biotechnologies associated with marine genetic resources will be created alongside benefit-sharing agreements that will have built capacity globally. By 2040, this interconnected network of regional centres might not only

have generated monetary benefits, but also distributed capacity to employ genomic technologies for a wide range of applications in human and planetary health. The utilization of marine genetic resources techniques in setting conservation priorities, monitoring and establishment of networks of marine protected areas (MPAs) will also indicate that the legal frameworks governing marine genetic resources have developed into effective, fit-for-purpose instruments, contributing to improved conservation outcomes.

Economy, markets and technology

As envisioned above, if States have access to marine biotechnology applications and can actively participate in their development, under the guidance of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), a coordinated international effort will be made to build scientific, technical and computing capacity by 2030 (Blasiak and others, 2020). In this scenario, industry embraces equity and inclusivity as norms of corporate practice, whereby it would publicly announce and share access and benefit-sharing agreements in line with the Nagoya Protocol and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Following the Agreement's entry into force in 2026, the first commercial product from areas beyond national jurisdiction will demonstrate flagship benefit-sharing and knowledge exchange, wherein all phases of research and development, commercialization and sales achieve full compliance with the Agreement and transparency principles and are aligned with scientific best practice. In addition, long-term industry partnerships with the regional centres of excellence could be developed with the aim of advancing the fair and equitable sharing of benefits from marine genetic resources.

As the range of benefits associated with marine biotechnologies becomes widely known, purely economic valuations are expected to increasingly shift to more holistic approaches. These would align with the findings of the values assessment framework of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which show a broad scope of the values related to nature, including intrinsic (nature for nature), instrumental (nature for society) and relational (nature for culture) values (IPBES, 2022; Krusberg and others, 2024; Islar and others, 2022). As the multiple benefits of marine genetic resources and marine biotechnology become part of public discourse, policymakers might incentivize the use of marine bioresources for biotechnology. In turn, industry could channel resources from successful commercialization efforts into foundations that support scientific research and conservation. By 2050, marine biotechnology could be considered a pillar of the sustainable, equitable and inclusive ocean economy, assessed not only in terms of revenues, but also in terms of its contribution to ocean conservation and sustainable development.

This aspirational pathway is one of many possible scenarios, and includes a number of uncertainties, assumptions and risks, including, for example, risks related to the pace and direction of marine biotechnology progress or the effective implementation of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. A business-as-usual pathway would be likely to carry suboptimal outcomes for the environment and for global equity, wherein the current rapid pace of climate change and biodiversity loss would likely continue or even escalate, with attendant but also uncertain socioeconomic and environmental consequences. The description of an aspirational pathway is intended to highlight ideal, sustainable and inclusive futures. The realization of this vision requires global and regional cooperation and the tackling of equity challenges, as outlined in part 5 below.

5. Social components

The advancement of marine biodiscovery is increasingly being recognized as a means to address certain Sustainable Development Goals. There are myriad potential societal benefits from the exploration of and utilization of marine genetic resources, from global health to the development of a sustainable and inclusive ocean economy. Potential benefits include the improvement of global public health (Salicrup and Fedorková, 2006), from addressing the control of zoonoses and the looming antimicrobial resistance crisis to vaccine development and pandemic preparedness (Gamberi and others, 2024; see also subsect. 5B). With antimicrobial resistance, infections become less treatable with current antibiotics, resulting in growing morbidity and mortality (Naghavi and others, 2024; Murray and others, 2022). An estimated 1.14 million people died of an antimicrobial-resistant infection in 2021, and new antibiotics for some of the most significant antimicrobial-resistant pathogens could save

11 million lives between now and 2050 (Naghavi and others, 2024). Most antibiotics currently in use are derived from soil bacteria, but there is significant potential for new antibiotics to be derived from marine environments (Barbosa and others, 2020; Tortorella and others, 2018), especially the deep sea, given the extreme conditions and the increased likelihood that such antibiotics could be derived from undiscovered chemical classes, and therefore act against current antimicrobial-resistant pathogens. This is also true for the most promising alternative to antibiotics, phage therapy (Gordillo and others, 2019), as there are large reservoirs of bacteriophage viruses in marine environments (Breitbart and others, 2018). Alongside deep-sea sediments, another potential source of bacteriophages is the bacteria that form elements of the microbiomes of sponges and other marine animals. The recovery of bacteria from these environments allows for the investigation of their genomes, which can reveal the presence of biosynthetic gene clusters responsible for the production of bioactivity. Some marine-derived bacteria have been shown to be rich in such biosynthetic gene clusters, illustrating their potential as marine natural products (Hesketh-Best and others, 2023).

A sustainable and inclusive ocean economy is one that provides social and economic benefits for current and future generations through its ability to protect, maintain and restore marine biodiversity (Hassanali, 2022). The global blue economy, now known as the sustainable and inclusive ocean economy, has been estimated at $2.5 trillion a year (WWF, 2025). Marine biotechnology offers significant growth potential due to increasing demand for sustainable resources, recent technological advancements, including in molecular techniques, and employment opportunities (Organisation for Economic Co-operation and Development, 2017; Daniotti and Re, 2021). For example, the global marine biotechnology sector creates an estimated 200,000 jobs annually (Rademaekers and others, 2015). Marine biotechnology can therefore support the sustainable development and economic growth of States, including through its potential to address social, economic and environmental challenges (Querellou and others, 2009).

The quantification of the marine biotechnology sector's economic value is challenging, however, due to the lack of a robust economic activity classification system globally for marine biotechnology enterprises. Current estimates of the global market value of marine biotechnology range from 2.5 billion euros and 3.9 billion euros in 2021 (Market Research Future (MRFR), 2024). The medical and pharmaceutical sectors are at the forefront of marine biotechnology, and vaccine development (Gamberi and others, 2024) is expected to contribute substantially to the sector's future growth. These trends reflect the fact that pharmaceuticals and medical applications tend to have high added value (European Commission, 2024). Other high-value applications from marine genetic resources include nutraceuticals, cosmeceuticals and biomaterials, as well as climate and agricultural mitigation applications (Blasiak and others, 2021). Revenues from just five marine-derived drugs (Adcetris, Halaven, Lovaza, Prialt and Yondelis)[2] were found to total over $1 billion per annum (Blasiak and others, 2022; Ottaviani, 2020). Other high-value marine genetic resources include the marine-derived drugs Zovirax and Cytarabine (Ara-C), both derived from the Caribbean sponge, *Tectitethya crypta* (Guilloux, 2018; Lloyd-Evans, 2005) and polymerase enzymes derived from archaea found in hydrothermal vents (e.g. *Pyrococcus furiosus*) and widely used in research and biotechnology (Juniper, 2013).

The benefits of marine genetic resources to society go far beyond monetary valuations (Krusberg and others, 2024). Beyond biotechnology, research on genetics/genomics, such as species diversity and population connectivity, provides insights on ecology and evolution (Jeffery and others, 2022). Because of the unique conditions in which marine genetic resources survive, they can provide essential information about life on Earth and its evolution, as well as improve knowledge of marine biodiversity and the role it plays in the provision of ecosystem services. Such information informs conservation and environmental management. For example, knowledge of species ranges, dispersal potential and population connectivity allows for the design of ecologically cohesive, connected networks of MPAs (Hunter and others, 2024). Non-monetary benefits of equitable marine scientific research (elements of which include the sharing of data, samples and knowledge) can build capacity as well as knowledge with respect to marine biodiversity,

[2] Adcetris is derived from the marine mollusc *Dorbella auricularia* and is used to treat Hodgkin Lymphoma; Halaven is derived from the *Lissodendoryx* marine sponge and is used to treat breast cancer; Lovaza is made from omega-3 fatty acids of fish oils and is used to lower high triglyceride levels; Prialt is derived from the cone snail *Conus magus* and is used to treat chronic pain; and Yondelis is derived from the marine tunicate *Ecteinascidia turbinata* and is used to treat soft tissue sarcoma.

ecosystems and evolution, with improved outcomes for conservation (Harden-Davies and others, 2020, 2024; Rabone and others, 2025; Guilhon and others, 2025).

One primary concern related to utilizing marine genetic resources and biodiscovery activities is the potential impact on marine ecosystems, particularly if products are developed that require a continuous supply of biological materials (Krusberg and others, 2024). To date, however, marine biotechnology has depended on the small-scale collection of samples to discover new molecules that are subsequently synthesized, avoiding further harvesting that may be unsustainable due to low natural abundance or other environmental concerns. Such collection efforts are consistent with general biological sampling principles, for example those employed by taxonomists with the underlying aim of better understanding marine ecosystems, and are subject to the same norms of best practice to minimize ecosystem harm (Hope and others, 2018; Beattie and others, 2011). For example, biodiscovery from microbes can be carried out sustainably if the bacteria can be cultured in the laboratory, avoiding the need to repeatedly sample potentially sensitive environments (Krusberg and others, 2024). By contrast, some products still require the harvesting of wild organisms. For example, high-purity polyunsaturated fatty acids for heart medications are obtained from marine species such as krill (Caffrey and others, 2023). Aside from this medical application, krill and other species are targeted for nutraceuticals by industrial-scale mesopelagic fisheries, giving rise to major concerns regarding sustainability and food web impacts (Fjeld and others, 2023).

Equity

Diverse narratives of a blue economy have emerged, but crucial to most framings is that equity is a guiding motivation for transitioning to an economy that is both sustainable and inclusive (Cisneros-Montemayor and others, 2021; Österblom and others, 2023). In the context of marine genetic resources, the fair and equitable sharing of benefits associated with use is set forth in both the Nagoya Protocol and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Despite regulatory expectations and emerging norms of best practice (Blasiak and others, 2019; Rabone and others, 2019, 2025; Harden-Davies and others, 2024), achieving the aspirational vision of an equitable, sustainable and inclusive ocean economy set out in part 4 of this chapter presents significant challenges. Specifically, imbalances in capacity can lead to fewer opportunities for participation in all stages of the marine biodiscovery process, from accessing the open and deep ocean to conducting laboratory work, research and publication and even participation in scientific conferences (Harden-Davies and others, 2024; Krusberg and others, 2024).

Currently, the ability to conduct research on marine genetic resources is not equal across regions and States (Guilhon and others, 2025; Vierros and others, 2016). Unequal access to marine genetic resources is driven both by disparities in molecular biology and biotechnology expertise and limited access to oceanographic vessels and equipment (Harden-Davies and Snelgrove, 2020; Arnaud-Haond and others, 2011). The expertise to conduct discovery research exists in some centres in the global South, where the richest biodiversity is found with attendant increased likelihood of novel compounds (Harden-Davies and others, 2020). However, investment is required to strengthen capacity and retain trained staff in these global South centres and achieve fair and equitable sharing of benefits arising from this biodiscovery work (Zhivkoplias and others, 2025). To develop the regional centres of excellence in marine genetic resources and marine biotechnology research envisaged in part 4 of the chapter, major capital funding is required for infrastructure development, funding that also needs to be sustained for maintenance and development (Rabone and others, 2019; Collins and others, 2021). These networks could initially be established by developing in-country capacity, for example in sampling and bioinformatics, and progressing through strategic partnerships and joint funding towards the building of repositories and research infrastructure, ultimately leading to interconnected centres. Cooperation and aligned efforts at the regional and international levels (Hassanali, 2022) will prove instrumental.

One recent example of equitable and inclusive marine genetic resource development is a project based in Kiribati, a small island developing State that obtained its first-ever patent (U.S. Patent No. 11,878,057) in a collaboration with researchers based in the United States of America. The discovery of novel deep-sea bacteria was made with minimal environmental impact, requiring no additional sampling beyond normal exploration efforts (Gauthier and others, 2021). Furthermore, the subsequent experiments and inventions do not require any further visit to, or extraction from, the deep sea, as the bacteria can be cultured in the laboratory. These novel bacteria were discovered in filtered water and tissue samples of benthic organisms, then cultured in a laboratory

environment, where they can be maintained in long-term storage. Innovations from these novel, lab-cultured bacteria were patented with named inventors from both Kiribati and the United States (Rotjan and others, 2024). The United States-based institutions covered the full patent fees, but the majority ownership of the patent rests with the Government of Kiribati. While no monetary benefits have yet been realized, the patent itself may be beneficial for conservation outcomes, since this discovery and subsequent invention were motivated by the conservation status of the Phoenix Islands Protected Area. Future conservation efforts in Kiribati and elsewhere will be strengthened by the realization that cutting-edge research can lead to industry pathways that involve equitable partnership. The balance between production and durable ocean protection is essential for enabling pathways for research and development on marine genetic resources that have a low environmental impact and high potential for economic value and conservation efforts (Kittinger and others, 2024). Such projects provide examples that can inform the development of a network of regional marine genetic resource repositories and research centres and the implementation of the provisions of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction on promoting marine scientific research, capacity-building and technology transfer.

Gender

Considering gender in relation to the use of marine genetic resources and biotechnology is important to achieving equity and the Sustainable Development Goals (Österblom and others, 2023; see also subsect. 5B, chap. 6). However, data on gender are scarce, especially for emergent sectors such as marine biotechnology when compared with traditional sectors of the maritime industry (Ituarte-Lima and others, 2025). Although gender inequality in marine biotechnology has been noted in the literature (Kitada and others, 2015), a lack of available data impedes informed analysis. When examining participation in marine scientific research, persistent gender bias patterns have been reported for European Union marine sciences and conservation (Giakoumi and others, 2021; Lima and Rheuban, 2022). The situation is more acute for women in the global South, but, again, data are lacking (Shellock and others, 2022). Fundamental issues of women's safety at sea while conducting scientific research (including within industrial contexts such as fisheries or oil and gas exploration) have also been raised in the literature, which shows that multiple factors contribute to a challenging work environment (Amon and others, 2022; Johannesen and others, 2022, 2025; Maia and others, 2024). Implementing frameworks to address fundamental equality issues including work environments at sea, particularly for women of the global South, is needed to advance gender equity (Amon and others, 2022; Johannesen, 2025).

More broadly, recommendations are being put forward at the United Nations and OECD to address gender equality in marine scientific research and to acknowledge the contributions of women and girls in marine conservation efforts (IOC-UNESCO, 2024). There have been calls to mainstream gender equality in legislation and policy frameworks to promote the creation of better employment opportunities for women across the blue economy (United Nations Entity for Gender Equality and the Empowerment of Women (UN-Women), 2020; Rahaman and others, 2024). However, these policies are not yet widespread in ocean-related activities, including those directly linked to marine genetic resources, such as marine biotechnology, where data remain scarce. Examples of women's participation in the blue economy in developing countries include women-led small-scale local fisheries and aquaculture in sub-Saharan Africa and the Indian Ocean Rim, with outcomes both positive and more equivocal, which underscore the need to support women's active participation (UN-Women, 2020; FAO, 2020). Enhancing women's roles in sustainable and innovative uses of marine genetic resources would contribute to a more equitable blue economy, alongside efforts to address the root causes of gender inequalities, collaborate with men and boys to challenge stereotypes and create conducive environments for women-led initiatives in the ocean space (IOC-UNESCO, 2024).

Traditional knowledge

The traditional knowledge of Indigenous Peoples and local communities associated with the management of marine resources, the understanding of species behaviour and medicinal applications dates to ancient times, with references in Indian, Chinese, Greek and Arabic texts (Voultsiadou and Vafiis 2007; Gopal and others, 2008). The Pacific region in particular has a rich tradition of traditional knowledge and cosmologies that directly relate to marine genetic resources (Hau'Ofa, 2008; Mulalap and others, 2020). Traditional knowledge has long been and continues to be vital to the conservation and sustainable use of the ocean and marine genetic resources (Mulalap and others, 2020). There is a growing focus on integrating traditional knowledge into ocean governance

and management (Pena-Neira and Coelho, 2025). Studies have shown that marine species used in traditional medicine belong to groups rich in bioactive natural products, namely sponges, cnidarians, molluscs, echinoderms and tunicates, pointing to the potential of traditional knowledge on marine species for the discovery of novel bioactive compounds (Herbert and others, 2003). A recent example of traditional knowledge and marine genetic resources is the oyster *Crassostrea (Magallana) saidii*, a species first identified by traditional knowledge and maintained as a separately managed fishery for over 120 years before it was formally described (Sigwart and others, 2021b). The local fishers could distinguish the "new" species from a co-occurring congener consistently, but scientists could not; the fishers' identifications were 100% accurate, as confirmed by DNA barcoding and morphometrics (Sigwart and others, 2021b).

However, links between scientific discovery associated with marine genetic resources and traditional knowledge are rare, in large part due to a disconnect between scientists undertaking biodiscovery research and the Indigenous Peoples and local communities who hold the knowledge. Furthermore, there is a great disparity between the holders of traditional knowledge and scientists in the global North in terms of capacity to explore and utilize marine genetic resources (Armitage and others, 2020). In addition, Western science and traditional knowledge follow different epistemologies in terms of knowledge production. While the former relies on rigorous methodological approaches and generalizations, the latter is localized and tied to the experiences, observations and practices passed down through generations, which are often tied to cultural, ecological, medicinal, social, agricultural and spiritual practices (Hockings and others, 2019). For medicinal examples, differences between traditional knowledge and scientific knowledge in relation to marine genetic resources arise because traditional knowledge systems encompass not only medicinal uses but also the social-spiritual dimensions of traditional medicine that cannot be readily translated into scientifically evaluated and medically approved patent medicines (Williams and Whiting, 2016). This disconnect raises ethical and legal challenges with respect to benefit-sharing, as researchers may lack awareness of associated traditional knowledge and communities may face challenges in accessing information, organizing and navigating access and benefit-sharing negotiations. Furthermore, inadequate legal frameworks exist for recognizing the knowledge systems of Indigenous Peoples and local communities and protecting the intellectual property rights of traditional knowledge holders. This is magnified by the fact that traditional knowledge systems and cosmologies are often held in oral rather than written records and across communities and geographical boundaries, especially in the case of marine species. Moreover, traditional knowledge is not bound by the legal fiction of jurisdictions under international law (Menime and others, 2022). The governance of traditional knowledge falls under the Convention on Biological Diversity for marine genetic resources from areas within national jurisdiction and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction for the marine genetic resources of areas beyond national jurisdiction. Benefit-sharing under the Convention on Biological Diversity may involve bilateral agreements between the Indigenous Peoples and local communities of provider States and resource recipients. This approach facilitates direct benefit flows to traditional knowledge holders. To harmonize legal frameworks governing marine genetic resources and to support the fair and equitable sharing of benefits, facilitating the connection between traditional knowledge and scientific research could foster more inclusive biodiscovery and innovation (Rabone and others, 2025; Pena-Neira and Coelho, 2025).

6. Governance

Key legal frameworks governing the fair and equitable benefit-sharing of marine genetic resources and digital sequence information include the Nagoya Protocol under the Convention on Biological Diversity and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, for areas within and beyond national jurisdiction respectively. Over the past decade, challenges linked to the effective implementation of the Nagoya Protocol have been identified (Laird and others, 2020; Prathapan and others, 2018). While these instruments have been ratified by many States, capacity constraints mean that many of these States have not yet implemented relevant administrative procedures (Ivey and others, 2023). The bilateral structure of the Nagoya Protocol necessitates navigation of the legislation on a country-by-country basis, which can be burdensome for users (Laird and others, 2020; Emery and others, 2025). Work is ongoing under the auspices of the Convention on Biological

Diversity to address some of these challenges. In relation to digital sequence information, there has been a shift towards a more harmonized approach to benefit-sharing with adoption of the multilateral mechanism on digital sequence information and the creation of the Cali Fund for the Fair and Equitable Sharing of Benefits from the Use of Digital Sequence Information on Genetic Resources (Conference of the Parties to the Convention on Biological Diversity decision 16/2), a global benefit-sharing mechanism (Convention on Biological Diversity, 2024; Sett and others, 2024; Scholz and others, 2022). There is a need for coordination across the Convention and its Nagoya Protocol (including on digital sequence information multilateral benefit-sharing) and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. More broadly, harmonization across agreements can support global commitments on conservation and the sustainable use of biodiversity and align with benefit-sharing targets under the Kunming-Montreal Global Biodiversity Framework, adopted at the fifteenth Conference of the Parties to the Convention on Biological Diversity in December 2022. At the time of writing, with rapid recent ratifications by States, the Agreement has already reached the threshold for entry into force, surpassing expectations (Blasiak and Jouffray, 2024). However, national and institutional capacity varies widely across States and regions, with some at risk of being left behind (Ardron and others, 2025; Rabone and others, 2025; Gjerde and others, 2022). For current and future generations to benefit equitably from marine genetic resources in areas beyond national jurisdiction, as anticipated under the Agreement, legislative and institutional preparations will need to begin now.

Adopted in June 2023 and entering into force in January 2026, the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction addresses a package of objectives geared towards achieving the conservation and sustainable use of biodiversity beyond national jurisdiction. The objectives relevant to marine genetic resources include fair and equitable benefit-sharing, capacity-building, knowledge generation and marine technology transfer (art. 9). The Agreement applies to activities relating to the collection and use of marine genetic resources and digital sequence information sourced from areas beyond national jurisdiction after the entry into force of the Agreement, excluding fishing regulated under international law and fish or other living marine resources known to have been taken in fishing and fishing-related activities from areas beyond national jurisdiction (art. 10). The Agreement applies to the utilization of marine genetic resources and digital sequence information collected or generated before its entry into force unless a Party expresses an exception in writing (art. 10 (1)). Such activities can be carried out in areas beyond national jurisdiction by all Parties, regardless of their geographical location, and by natural and juridical persons under their jurisdiction (art. 11 (1)). Relevant activities must be carried out with due regard for the rights and legitimate interests of coastal States in areas within national jurisdiction, as well as those of other States active in areas beyond national jurisdiction (art. 11 (3)). The interests of all States must be taken into account, particularly the interests and needs of developing States (art. 11 (6)).

Specific notification requirements have been created with respect to the collection and utilization of these resources. Parties are required to take the necessary legislative, administrative or policy measures to ensure that information is provided to the clearinghouse mechanism at various stages of the process. Article 12 (2) (a)–(j) lists the information that must be provided six months prior or as early as possible before the in situ collection occurs, after which time a standardized batch identifier shall be generated (art. 12 (3)). This is a persistent (or permanent) unique identifier that follows marine genetic resources and digital sequence information through the research and commercialization journey. Although this is a grouping identifier associated with a whole research cruise or equivalent "batch", its utility rests on the fact that it can be used to identify research, development and commercialization activities involving marine genetic resources and digital sequence information, making this a "light touch" end-user traceability mechanism (Lawson and others, 2025; Rabone and others, 2025; Thambisetty and others, 2023, 2025). After in situ collection has taken place, Parties are required to ensure that information regarding, inter alia, where collected marine genetic resources and digital sequence information will be deposited, the geographical location from which marine genetic resources were collected and, to the extent possible, the findings from the activities undertaken, is provided to the clearinghouse mechanism, together with the standardized batch identifier, as soon as it becomes available, but no later than one year from the in situ collection date (art. 12 (5)). Once marine genetic resources and digital sequence information is used, including in commercialization, Parties must ensure that the following information, inter alia, is also provided to the clearinghouse mechanism, together with the standardized batch identifier: publications, patents granted and products developed; modalities for the management of access to collected marine genetic

resources and digital sequence information; and details of the sales of relevant products (art. 12 (8)).

Regarding benefit-sharing, the Agreement makes a direct link between benefits and how they should be used by providing that benefits, both monetary and non-monetary, must be shared in a fair and equitable way in order to contribute to the conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction (art. 14 (1)). Regarding non-monetary benefit-sharing, the Agreement provides extensive examples (see art. 14 (2) (a)–(h)). Parties are also required to take reasonable measures to ensure that marine genetic resources and digital sequence information subject to utilization are deposited in publicly accessible repositories and databases as soon as they become available, but no later than three years from the start of such utilization (art. 14 (3)). Reasonable conditions can be placed on access to marine genetic resources and digital sequence information, such as the need to protect the physical integrity of the marine genetic resources and reasonable maintenance and access costs (art. 14 (4)). Furthermore, opportunities for access on fair and most favourable terms may be provided to researchers from developing States (art. 14 (4)). Concerning monetary benefit-sharing, the Agreement provides that such benefits must be shared through the financial mechanism established under the Agreement under article 52, with modalities to be decided by the Conference of the Parties, taking into account the recommendations of the access and benefit-sharing committee to be established under the Agreement (art. 14 (7)).

7. Summary

Marine genetic resources and the use of marine biotechnology hold significant, but as yet untapped, research and development promise. Rapidly advancing techniques will change the research landscape, however, and could greatly support conservation measures, monitoring efforts and the design of MPAs that underpin global commitments for conservation of biodiversity. Research and development of marine genetic resources and marine biotechnology provide a timely opportunity to address urgent global challenges in planetary and human health. If applied in an integrated, inclusive and interdisciplinary way, including through the development of regional marine genetic resource centres of excellence and leveraging existing resources and coordinating input from local, regional and global levels, such efforts have the potential to improve equity in research and, more broadly, across society.

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Chapter 6
Shipping

Key points

- Maritime shipping is vital to the global economy, handling over 80% of global trade by volume. Developing economies, particularly in Asia, play a significant role in this sector. The industry's economic expansion has led to substantial environmental impacts, reinforcing the urgency of sustainable solutions.
- Shipping is a major source of environmental pollution, including chemical, biological and energy-related contamination, as well as greenhouse gas emissions. In addition to these ship-generated pressures, port activities also negatively affect marine ecosystems and coastal communities, intensifying issues such as eutrophication and habitat disturbance, and have an adverse impact on human rights.
- Decarbonization of the shipping sector is crucial, as greenhouse gas emissions from ships contribute about 3% of global emissions. Strategies such as zero and near-zero fuels (e.g. liquefied natural gas, methanol or hydrogen), improved ship designs and policy frameworks, are aimed at reducing emissions, but the associated costs, expansion of infrastructure and fuel cycle emissions remain significantly challenging.
- Shipping affects human health through emissions that, for example, affect coastal communities. In addition, the maritime sector faces issues such as crew safety, occupational health and gender equity. Regulatory frameworks (e.g. low-sulfur fuel standards) are aimed at reducing human health risks, although unintended environmental trade-offs exist.
- Global regulations, primarily developed by the International Maritime Organization (IMO), are central to governing shipping's environmental impact. Conventions such as the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto, and as further amended by the Protocol of 1997 (MARPOL), and the International Convention for the Control and Management of Ships' Ballast Water and Sediments 2004 set standards to reduce pollution and invasive species spread. Continued updates and enforcement are essential for sustainable ocean management and climate goals.

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1. Introduction

Maritime shipping refers to the transportation of goods and passengers via sea. This sector, which includes both vessels and landside support infrastructure (i.e. seaports), plays a dominant role in the ocean economy's contribution to global gross domestic product (GDP), and its importance in advancing the sustainable development agenda cannot be understated (United Nations Trade and Development (UNCTAD), 2023). The present chapter contains a discussion of environmental pressures resulting from a growing number of vessels active on the world's oceans, as well as potential pathways and policies that can lead towards a more sustainable shipping sector. Furthermore, the human dimensions of shipping, such as safety, occupational health and human rights, are addressed.

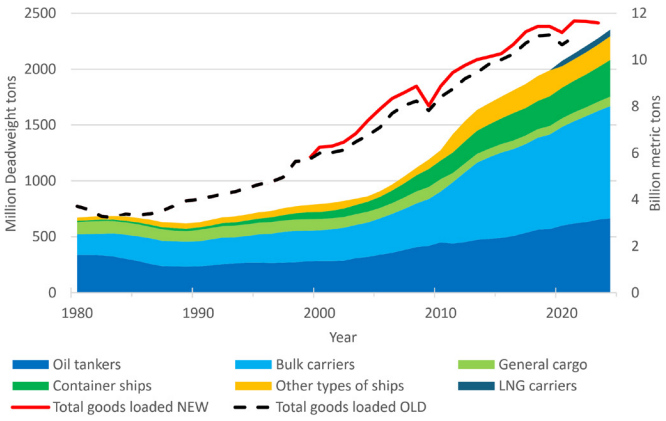
International shipping activities reflect global economic and geopolitical situations. The impacts of the 2008–2011 financial crisis, followed by the 2020–2023 coronavirus disease (COVID-19) pandemic, marked the first and second World Ocean Assessments respectively (see subsect. 5B, chap. 7). As the global economy recovers from the pandemic, international shipping has rebounded, albeit with several dampening effects as a result of geopolitical events, in the period 2022–2025, thereby demonstrating the impact of geopolitical events on shipping and the marine environment (see sect. 4, chap. 1).

Globally, shipping accounts for over 80% of the international trade volume, making it an important part of every nation's economic growth (UNCTAD, 2024). Maritime transport, ports and warehouses, together with other ocean economic activities, have been growing globally for the past 25 years, often outpacing the growth of the global economy (Organisation for Economic Cooperation and Development (OECD), 2025).

The annual amount of goods loaded has doubled over the past three decades, with over 11 billion metric tons moved by over 105,000 ships. Of that growth, 92% is attributed to dry cargo (carried by bulk carriers, container ships and general cargo ships) (UNCTAD 2024; see also figure I). This shipping activity occurs across the world's oceans (figure II) and through a complex network of seaports and routes with over 4.6 million port calls in 2023.[1] Those seaport activities accounted for 13% of the global value added of ocean industries and are projected to increase to 16% (exceeding $3 trillion) by 2030 (UNCTAD, 2023). Developing economies dominate international shipping, with Asian seaports accounting for 50% and 30% of goods discharged and loaded, respectively (UNCTAD, 2023).

Figure I

Upward trend in the development of international maritime trade as annual goods loaded worldwide (billions of tons) and the world shipping fleet by vessel type (millions of deadweight tons)

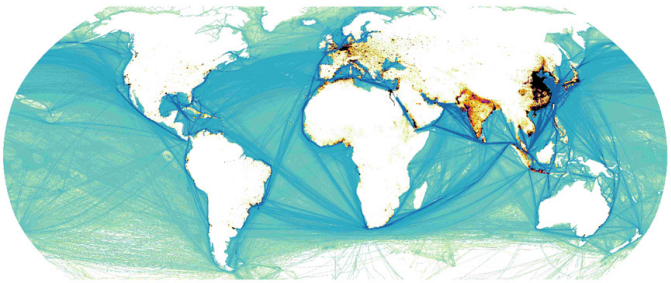


Source: UNCTAD Data Hub.

Note: In 2025, UNCTAD changed its methodology applied for data from the year 2000; accordingly, both the new and the previous data available are included.

Figure II

Emissions over water from world shipping routes and the related human health impacts on land



Source: Sofiev and others, 2018.

Note: Bolder lines correspond to major routes. American sulfur emission control areas have been effective in reducing human health impacts in North America.

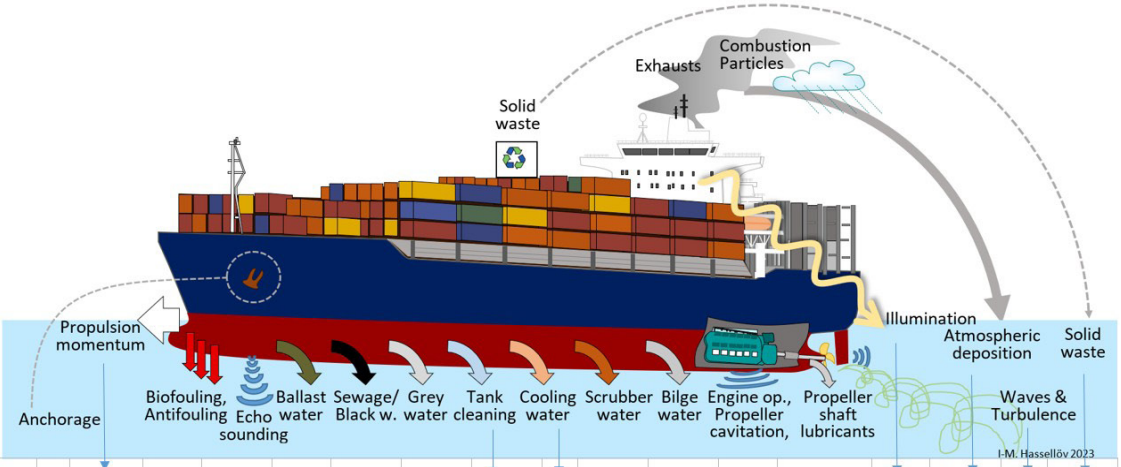
[1] See https://unctadstat.unctad.org/datacentre/dataviewer/US.PortCallsArrivals.

Environmental pressures from shipping and related port activities include chemical, biological and energy pollution and physical disturbance from anchoring and dredging. Climate change introduces additional pressures by shifting marine habitats at times into shipping lanes and by making possible the opening of new shipping routes in the Arctic. In the second *World Ocean Assessment*, it was reported that, while shipping activities continued to increase, there had been fewer shipping accidents leading to reduced oil pollution into seas; in addition, more stringent global or regional regulations to reduce sulfur oxides and nitrogen oxides have led to decreased air pollution in the atmosphere.

In the current *Assessment*, a comprehensive framework is used to assess the environmental pressures and impacts of shipping and their relevant international regulations (figure III). Besides impacts to natural ecosystems, shipping emissions also impact human health (Sofiev and others, 2018; see also subsect. 5B, chap. 2).

Since the publication of the second *World Ocean Assessment* in 2021, efforts have continued to enhance the sustainability of the shipping sector. They include the development of international and regional regulations and the advancement of technological solutions such as emissions abatement (Inal and others, 2022), hybrid sources of renewable energy (e.g. solar, wind, fuel cells), zero and near-zero fuels (e.g. liquefied natural gas, methanol) (Pan and others, 2021), hull and engine design and life-cycle cost management. Advances have also been made in shipbuilding, an area in which recycling and the promotion of a "circular economy" have taken hold. The Blue Ports Initiative establishes a strategy for seaports to integrate economic efficiency with social responsibility and environmentally friendly practices into port activities, operations and management. Assessments on how the shipping sector may contribute to the sustainable development agenda are presented in part 3 below on sustainability pathways. Regional and international shipping regulations adopted since the publication of the second *World Ocean Assessment* are presented under part 4 below.

Figure III
Pressures from ship activities on the marine environment



Pressure																	
Collision (birds, mammals, ice habitats)		X															
Non-indigenous species (NIS)			X		X	X	X										X
Contaminating compounds			X		X	X	X	X	X	X	X		X		X		
Nutrient and organic enrichment						X	X	X		X					X		X
Acidifying compounds								X		X					X		
PM & marine litter, incl. microplastics			X			X	X			X	X				X		X
Artificial light pollution														X			
Noise and energy pollution	X	X		X								X				X	
Physical Seabed Disturbance	X															X	
Shipping regulatory framework			AFS		BWMC	MARPOL Annex IV	MARPOL Annex IV*	MARPOL Annexes I, II & V		MARPOL Annex VI	MARPOL Annex I		MARPOL Annex I		MARPOL Annex VI		MARPOL Annex V

Source: Modified from Jalkanen and others, 2021.

Abbreviations: AFS, International Convention on the Control of Harmful Anti-fouling Systems on Ships; BWMC, International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004; PM, particulate matter.

Note: Grey water is often mixed with sewage, implying that annex IV, indicated by * in the table, will indirectly apply.

2. Environmental pressures and the impacts of shipping activities

The positive impacts of shipping are well-known and include economic growth, job creation and new investments in research and development. However, ships have an array of subsystems (see columns in figure III) that exert pressures on the marine environment (see rows in figure III) (Jalkanen and others, 2021; Shu and others, 2022; Ytreberg and others, 2022). The present part of the chapter contains a discussion of these pressures in four primary categories: chemical pollution, biological pollution, greenhouse gas emissions and energy pollution (including hydrodynamics, noise and light). Although the focus is on impacts from vessels in the present chapter, it is recognized that additional impacts from seaports are important to consider when it comes to the degradation of coastal areas and soil pollution.

Chemical pollution

Ships continue to emit large amounts of sulfur and nitrogen oxides into the environment, which cause acidification and human health impacts. This has been mitigated in recent years with the use of low-sulfur fuels and pollution-control technologies, although these reductions often come with climate change trade-offs (Sofiev and others, 2018; Yuan and others, 2024). In the case of exhaust gas cleaning systems (scrubbers), another trade-off is increased contaminant load into the marine environment (Lunde Hermansson and others, 2021). Currently, the approximately 5,000 ships equipped with scrubbers, which allow for the continued use of cheap heavy fuel oil, account for 25% of the global marine bunker fuel consumption and a major share of metals and organic contaminants from shipping (Lunde Hermansson and others, 2024), in addition to particulate matter entering the marine environment (Anders and others, 2025; Gondikas and others, 2025).

Ships also leach metals and other chemicals into the marine environment through anti-fouling paint and cooling water where sacrificial anodes are used. Indeed, these are the largest sources of copper and zinc from ships (Amara and others, 2018). Organotin compounds and cybutryne in ship anti-fouling paints have been prohibited since 2008 and 2023, respectively, by the International Convention on the Control of Harmful Anti-fouling Systems on Ships (Marine Environment Protection Committee (MEPC), 2021c). Tributyltin, despite being banned in 2008 due to slow degradation and previous high pollution levels, is still found at very high levels in many harbours and hotspots throughout Europe, Asia, and North and South America (Beyer and others, 2022). Metals and organic contaminants also occur in treated and untreated bilge water and propeller shaft lubricants. For example, in the Baltic Sea, maritime shipping is estimated to be a major contributor of copper (almost 40% of total load when compared to all other sources, such as riverine run-off, atmospheric deposition and point sources on land), vanadium (12%), phenanthrene (9%) and anthracene (8%) (Ytreberg and others, 2022). Studies have indicated that shipping can be a significant contributor of contaminants in other estuarine and coastal areas with intense ship traffic and limited water exchange (Aghito and others, 2025; Calgaro and others, 2025).

Nitrogen oxides in ship exhausts deposited on the sea surface will, together with nitrogen and phosphorus in ship-generated food waste, untreated sewage and grey water, contribute to eutrophication (Raudsepp and others, 2019). The resulting excess biomass, together with directly discharged organic matter from food waste and sewage sludge, is deposited on the sea floor, where it can cause oxygen depletion (Diaz and Rosenberg, 2008; Wilewska-Bien and others, 2016).

Plastic litter is recognized as a major environmental problem. Even though dumping of plastic material as waste has been prohibited by the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and the 1996 Protocol to the Convention, and even though discharge of plastic as garbage is regulated by annex V to MARPOL, shipping and fisheries industries are still recognized as marine sources of plastic litter. Further work to increase the availability and adequacy of port reception facilities for the collection of plastics is vital for tackling this issue; as a result, IMO adopted a marine litter strategy in 2021. There is emerging but inconclusive evidence that anti-fouling paints may be an important source of microplastics in the sea (Dibke and others, 2021). In summary, shipping contributes to cumulative pressure from contaminants, eutrophying and acidifying substances to the marine environment (see sect. 4, chap. 6). Chemical pollution due to shipping also threatens a broad range of human rights, including the rights to a clean, healthy and sustainable environment, life, health, food, water and sanitation, and safe and healthy working conditions (see A/79/163).

Biological pollution

Ships are the primary vector spreading non-indigenous marine species on hulls, in niche areas or in the ballast water of ships (Bailey and others, 2020; see also sect. 4, chap. 6). Ballast water treatment systems use mechanical, physical, chemical, biological or combined treatments (Sayinli and others, 2022) and have been regulated by the Ballast Water Management Convention (IMO, 2004) since 2017. Hull biofouling also increases the surface roughness of a ship's hull (i.e. its frictional resistance, shear stress and weight), thereby increasing fuel consumption and, as a result, emissions to maintain the speed profile. Shipping is suggested to have a more pronounced effect on marine invasions than climate-driven environmental changes (Sardain and others, 2019).

Greenhouse gas emissions

Shipping accounts for about 3% of global greenhouse gas emissions, with a projected increase between 90% and 130% of 2008 levels by 2050, following increased maritime trade under a business-as-usual scenario (IMO, 2020a). These emissions are considered to contribute significantly to global warming and climate change, causing significant impacts on the environment. A number of technical and economic approaches are being taken to address these emissions, such as the development of a goal-based marine fuel standard regulating the phased reduction of the marine fuel's greenhouse gas intensity and a pricing mechanism for maritime greenhouse gas emissions (MEPC, 2023d).

One major impact of global warming is the reduction of Arctic sea-ice extent and thickness, which reduces ice albedo and leads to even more global warming and concomitant ice reduction (Intergovernmental Panel on Climate Change (IPCC), 2022). With reduced ice, more ships are expected to travel to the Arctic during certain months of the year (Corbett, Lack and others, 2010). Ships navigating in Arctic waters are required to comply with the International Code for Ships Operating in Polar Waters (Polar Code) and related regulations relating to the safety of navigation, the protection of the marine environment and manning and training for seafarers (MEPC, 2015). By 2050, polar class 6 and non-ice-class vessels will likely have access to more route options through the North-West Passage, the Northern Sea Route and the Transpolar Sea Route (Smith and Stephenson, 2013; Melia and others, 2016; Theocharis and others, 2018). The use of Arctic shipping routes will reduce travel time and the consumption of fossil fuels and the associated carbon dioxide (CO_2) and other emissions; for example, using the North-West Passage can reduce CO_2 emissions by 49% to 78% compared with conventional shipping routes (Schøyen and Bråthen, 2011). However, other ship emissions, such as black carbon, may create near-term environmental and climate concerns as these Arctic routes are opened (Corbett, Lack and others, 2010; Corbett, Winebrake and Green, 2010). Shipping activities in Arctic waters should be carefully managed to protect the Arctic's sensitive marine ecosystem and consider the interests of Indigenous Peoples.

Energy pollution

Energy from ship propulsion can physically affect the marine environment. Depending on water depth, vessel speed and the distance from the ship's course (Huang and others, 2023), ship-generated waves can account for large portions of the total wave energy in confined waterways and coastal areas, where ships also produce a localized depression in the water that can drive strong currents (Dempwolff and others, 2022). The waves can cause morphological changes in nearby coastal slopes, damage infrastructures (Grue, 2017; see also sect. 4, chap. 6) and disturb the biodiversity of marine habitats (Gabel and others, 2017). Propeller action is the main source of turbulence, which can extend over considerable distances and contribute to oceanic mixing (Nylund and others, 2023). In methane-rich coastal environments, ship passages can trigger substantial methane emissions from the bottom water to the atmosphere. For example, fluxes of 11.1 mmol per m^2 per day, or 20 times higher than the surrounding background flux, were reported from the Neva Bay shipping lane (Nylund and others, 2025). Due to the significant impact of the propeller on ship efficiency, extensive research is focused on its optimization.

Ship-generated underwater noise, primarily from the hulls, engines and propellers of ships, may interfere with the ability of marine animals (such as whales, sea turtles or fishes) to navigate to preferred habitats to find food and mates, to communicate with each other or to avoid predators (Jones, 2019; Rako-Gospić and Picciulin, 2019). While it has been suggested that airborne noise pollution from ships could be reduced by the use of electric motors, which would also improve fuel efficiency, a recent study shows that underwater noise is not reduced from a fully electric ship (Andersson and others, 2024).

Light pollution from ships, an established but incompletely described type of pressure, can lead to the fragmentation or loss of ecosystems and a decline in

biodiversity. Artificial light affects species orientation, recruitment and reproduction, predation and communication. It mainly affects the functioning of nocturnal species. Symptoms include confusion and attraction or aversion to light sources (Carić and Mackelworth, 2014; Davies and others, 2014). In addition, seabirds attracted to artificial light can lose their way, crash into buildings, run out of food, become exhausted or be caught by predators (Merkel and Johansen, 2011). Predicting how fish will react to artificial light is difficult, as their ability to perceive light underwater depends on several variables, including the positioning of the light source in water or above and variation in species-specific response (Marangoni and others, 2022).

3. Sustainability pathways

Despite the significant environmental impacts of maritime shipping on the global environment discussed above, there are opportunities to find a more sustainable pathway moving forward that is in line with the 2030 Agenda for Sustainable Development. New technologies (such as sewage treatment systems) and operational changes (such as slow steaming and e-navigation) can reduce the amount of contaminants ships emit into the environment. New engine and hull designs can reduce noise pollution, and new advances in ballast water treatment can reduce the likelihood of invasive species transport. However, because of the critical importance of addressing climate change, the present part of the chapter is focused on sustainable pathways related to the decarbonization of the maritime shipping sector.

Decarbonization pathways

Greenhouse gas emissions from ships represent approximately 3% of global anthropogenic greenhouse gas emissions (IMO, 2020a), and policymakers and industry are focusing attention on reducing greenhouse gas emissions from international shipping (UNCTAD, 2023). IMO and its member States have taken significant steps in this regard, implementing new policies to reduce greenhouse gas emissions from ships (MEPC, 2023d). While the long-term effectiveness of these measures is uncertain, member States have adopted an ambitious greenhouse gas strategy that is aimed at reaching net-zero emissions from international shipping by or around 2050. The strategy includes reductions of at least 40% in the carbon intensity of international shipping, that is, the CO_2 emissions per transport work (IMO, 2020a), by 2030 compared with 2008 (MEPC, 2023b). These goals are aligned with Sustainable Development Goal 13 on climate change.

The decarbonization of international shipping will require the implementation of a variety of technical, operational, and behavioural changes in the international shipping sector (Winebrake and Corbett, 2010; IMO, 2020a; Kanchiralla and others, 2022). These changes will need to be induced through policy instruments that range from command-and-control directives (such as emissions standards and design indices) to market-based approaches (such as emissions fees or market-based credit systems). Existing policy instruments are focused on the technical and operational aspects of reducing emissions, such as mandating energy efficiency and carbon intensity standards (MEPC, 2023b). The draft amendments to annex VI to MARPOL, the "IMO net-zero framework", is awaiting adoption. Moreover, new technologies are being developed that have the potential to capture and store carbon from ships' exhaust (Kanchiralla and others, 2024). Another key to guiding decarbonization is the transparent measurement, reporting and verification of ship fuel consumption (Singh and others, 2016; Sabine and others, 2024). In 2016, IMO launched its data-collection system for this purpose (MEPC, 2016).

Finally, while the 2006 Stern Review on the Economics of Climate Change estimated that the cost of global inaction on climate change significantly outweighs the expected cost of coordinated global action, the cost of reducing greenhouse gas emissions from the international shipping sector is expected to be substantial and bears a risk of disproportional negative impacts, especially on developing countries, in particular small island developing States and least developed countries. UNCTAD (2023) reports that estimates show that decarbonizing the world's fleet by 2050 could require $8 billion to $28 billion annually and that the "infrastructure for 100% carbon-neutral fuels could need an even heftier $28 billion to $90 billion each year". If achieved, full decarbonization could double yearly fuel costs, driving the shipping industry to seek finance frameworks to achieve economic, environmental and social sustainability (Haugan and others, 2024). The present part of the chapter is focused on some of the more prominent decarbonization strategies being explored by the sector and contains a discussion of the opportunities and challenges of each strategy, with emphasis on the marine environment.

Zero and near-zero fuels and propulsion technologies

Many promising options exist for the use of zero and near-zero fuels as bunker fuel for ships. These fuels have a lower carbon intensity compared with conventional heavy fuel oil or other diesel-based marine fuels, and therefore could have a lower climate impact when used. The variety of fuels being considered includes methanol, ammonia, hydrogen, electricity and biofuels. The assessment of future fuel mixes is a complex task (Kanchiralla and others, 2024). However, the majority of existing life-cycle assessment studies of marine fuels lack transparent disclosure of the methodological choices and assumptions, and lack an uncertainty analysis, which suggests that they cannot provide clear guidance on the potential environmental impacts of marine fuels (Roux and others, 2024).

Two primary challenges associated with introducing these "clean" fuels into the global shipping sector are cost and access. With respect to cost, as many of these zero and near-zero fuels are priced considerably higher than conventional fuel oils, ship operators must be properly incentivized to spend more for them, either through policy mandates or economic incentives. With respect to access, many of these fuels, including hydrogen and ammonia, have immature landside supply chain and bunkering infrastructure that may also require extra safety measures. Moreover, it will be challenging to switch vessels to these fuels if there is no guarantee that refuelling options exist across the complex maritime transportation network used by them.

In addition, although many of the zero and near-zero fuels, such as ammonia, show significant promise in terms of reducing greenhouse gas emissions from vessels, there may be considerable greenhouse gas emissions that occur during the extraction, production and transportation of these fuels to bunkering outlets, as well as from unburned hydrocarbons, such as methane, that are emitted when used on board a vessel ("methane slip"). In addition, ammonia is known to be toxic to marine invertebrates, with growth inhibition, oxidative stress and immunological responses being the top three types of acute responses, and growth inhibition, nervous system injury and metabolic disorder dominating the chronic responses (Zhang, Li and others, 2023). However, under moderate ammonia stress, ecosystem complexity dampens effects, consistent with previously observed scale-dependent toxicity of ammonia on aquatic organisms (Liu and others, 2022). Ammonia as a nutrient pollutant is well-known, and any spill in areas sensitive to eutrophication will be detrimental (see sect. 4, chap. 6). Accounting for all these emissions as part of a total fuel cycle analysis is important (Kanchiralla and others, 2022). Greenhouse gas emissions from fuel extraction (or electricity production) through to end use are called "well-to-wake" emissions, and studies have shown that it is critically important to consider well-to-wake emissions when comparing fuels (Winebrake and others, 2019; MEPC, 2024e; Roux and others, 2024).

Nevertheless, opportunities exist for a variety of zero and near-zero fuels when considering the full well-to-wake greenhouse gas life cycle (Carr and others, 2024). Most promising are fuels that can be produced sustainably (i.e. through renewable means), as well as those that do not need massive infrastructure investment to be operationalized. Indeed, the order book for new vessels operating on zero and near-zero fuels shows over 400 ocean-going vessels investing in methanol, ammonia and battery-assistance, although it should be noted that these orders represent only a small fraction of the total number of vessels on order (ibid.). Continued assessment is needed to demonstrate how these fuels can be produced sustainably and operate effectively in the maritime sector.

In addition, it is imperative to address the safety issues related to alternative fuels, as well as ensure the necessary training of seafarers.

Operations and logistics

Another set of options for reducing the carbon intensity of the shipping sector is through modifications in operations and logistics, or how ships are deployed and used in global transport. Three opportunities that are particularly noteworthy are slow steaming, just-in-time arrival and e-navigation systems.

Slow steaming is when vessel speed on the water is adjusted as it moves goods from origin to destination. Since a vessel's fuel usage is exponentially proportional to its speed, slowing vessel speeds can have a dramatic impact on fuel use and emissions. Reducing speeds by 50% can lead to a 70% reduction in fuel use (Corbett and others, 2009). Although slow steaming is promising, it faces challenges as a long-term solution to decarbonization. For example, slow steaming leads to slower delivery times, which needs to be balanced against the general customer tolerance for longer transit times (Vakili and others, 2023); it may even be unacceptable for certain

commodities, such as fresh food (Dere and others, 2022). Slower deliveries without loss of service implies that vessels must be added to the global shipping fleet, which may offset the emissions reductions gains from slow steaming in the first place. In addition, the Asia-Pacific Economic Cooperation (APEC) (2019) has highlighted that the complexity of analysis of impacts of slow steaming for the economies of remote islands necessitates further studies to ensure that small island developing States are not negatively affected by, for example, global strategies for slow steaming. Nevertheless, for certain commodities that do not have a best-before date, slow steaming is a viable option for reducing greenhouse gas emissions.

Another existing option for reducing emissions from ships is the concept of "just-in-time arrival". This operational strategy addresses a common problem in the shipping sector, whereby vessels arrive at port but are unable to dock due to congestion, availability or other factors. When faced with such a situation, vessels anchor outside of port, burning fuel – sometimes for days – while they wait for an opportunity to dock. During this period, the on-board subsystems impact the marine environment (Argüello and others, 2022). Just-in-time arrival is designed to address this problem by providing real-time data to vessels under voyage so that they can adjust their routes or speeds according to their ability to dock at a destination port. While economic incentives exist that encourage the use of just-in-time docking, data exchange systems or port community systems must be made more robust for the practice to be taken up more holistically in the shipping sector, especially in small island developing States (World Bank, 2024). However, certain operational and market dynamics can work against just-in-time practices, such as when ships remain at sea to await higher cargo prices or when liquefied natural gas feeder vessels spend substantial time at sea simply to burn off gas to manage tank pressure, without performing any actual transport work (Hörteborn and Hassellöv, 2023).

Lastly, an important tool for making informed decisions regarding the safety and efficiency of ship operations is marine weather data, which comes from various sources, such as satellites, buoys, ships and ground stations (Miloslavich and others, 2024). The maritime industry is undergoing a digital transformation. E-navigation is a key component of smart shipping, as it integrates human engagement with navigational advancements and leverages technological achievements to improve safety and security at sea, enhance berth-to-berth navigation and protect the marine environment.

Ship design and retrofitting

Another approach to decarbonizing global shipping is through ship design and retrofitting. Since the early 2000s, IMO has been working with the shipping industry to improve the efficiency of ship operations. These initiatives have been focused on three primary areas: (a) the Energy Efficiency Design Index, which is an increasingly stringent energy efficiency metric per capacity mile (e.g. per ton-mile) on the basis of ship classification; (b) the Ship Energy Efficiency Management Plan, which is a mechanism for achieving greater efficiency in on-board energy management and includes tools to help to monitor energy use (MEPC, 2022a); and (c) the Energy Efficiency Existing Ship Index and the carbon intensity indicator rating, which went into force in 2022 and 2023, respectively, with the goal of providing a metric for energy efficiency and carbon emissions for existing ships that must be improved annually.

All three approaches are tools to help shipbuilders and operators find ways to reduce greenhouse gas emissions. These approaches are technology-neutral and do not dictate which energy efficiency measures or other technologies are required on board a vessel. Instead, they provide guidance and targets to the sector that can be met in a variety of ways. Energy-saving devices, such as wind-assisted propulsion systems, air lubrication systems, waste heat recovery devices and photovoltaic power generation, are all options that ship operators may explore (MEPC, 2021a).

The costs and benefits of these options are vessel-dependent and sometimes require sophisticated analysis that includes significant uncertainty and validation difficulty due to a lack of full-scale data. For example, recent evidence suggests that modelling uncertainties remain higher than the maximum net benefit typically offered by many energy-saving devices (Ponkratov, 2017; Andersson and others, 2022; Terziev and others, 2022). Given the risks involved, ship operators may be reluctant to implement some of these technologies without additional data validation and operational experience at full scale.

Circular economy ship recycling

Another consideration for sustainable pathways beyond decarbonization is how the sector deals with ships at

the end of their operational life, in line with the concept of "cradle to grave". By recovering steel, various metals and a wide range of used materials, the need for further extraction of natural resources is minimized. For steel, in particular, which accounts for up to 95% of a ship's weight, recovery through ship recycling can lead to a 70–90% reduction in the ecological footprint and environmental impact, in comparison with the production of ships from iron ores (Rahman and Kim, 2020). However, as many current recycled ships were built in an era with weaker environmental regulations, they can also contain a variety of hazardous and toxic substances, including asbestos, metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), glass wool and biocide anti-fouling coatings such as tributyltin. Unsustainable ship recycling operations and waste disposal poses environmental and health risks (Dey and others, 2021). The sustainability challenges in ship recycling are multidimensional and include corruption to circumvent environmental laws, for example when flags of convenience are used to allow obsolete ships to berth in ship recycling facilities in countries that have not ratified the relevant international conventions. In the global trade fleet, 61% of ships sport such flags, which allows developing countries with less stringent labour and environmental protection legislation to offer scuttling of obsolete ships or to offer long-term low-cost scrapping areas (Devault and others, 2017). Currently, the focus is on the sustainable recycling of ships, minimizing environmental impact and maximizing material recovery (Hiremath and others, 2015; Zhou and others, 2021; see also sect. 3). By taking a holistic approach to the life cycle of a ship, appropriate decisions during the design and construction of a ship (the "design for recycling" concept) and throughout its life cycle can contribute to reducing the environmental impact during the scrapping stage. This is the aim of the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009, which entered into force at the global level on 26 June 2025.

Ocean observation and monitoring

Effective and resource-efficient monitoring and ecosystem-based management strategies are essential for the conservation of marine ecosystems. Fixed-wing or mobile rotary-wing unmanned aerial vehicle remote-sensing platforms can be used to collect multidimensional marine data. These vehicles have been effectively used to monitor the marine environment for tasks such as oil spill detection, marine debris identification, algal bloom observation, carbon stock estimation, dissolved organic carbon (DOC) content detection and total suspended sediment assessment. Data on marine physics, chemistry and biology can be coordinated and collected by underwater gliders equipped with a variety of sensors. Unmanned surface vehicles reach various offshore destinations from the nearest shore. Numerous sensors are carried by them for important monitoring of atmospheric and marine environmental variables (Yuan and others, 2023). With the right sensors, maritime autonomous surface ships can operate autonomously or remotely to continuously measure ocean parameters. Satellite remote-sensing platforms can provide physical oceanography-related monitoring, detect oil spills and contribute to the monitoring of biological patterns. FerryBoxes, which are automated surface water monitoring systems that are fitted to ships' through-flow systems and equipped with various sensors, can collect data on physical, chemical and biological ocean parameters (Intergovernmental Ocean Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), 2024). The Voluntary Observing Ship (VOS) programme (see, e.g., https://vos.noaa.gov) depends on the volunteer participation of crew members and gathers information on weather observations that are valuable for climatologists. Lastly, automatic identification system (AIS) data, originally developed for enhanced navigational safety, are currently essential both for the assessment of environmental pressures with respect to shipping and for relating sensor data collected by ships (Calewaert and others, 2024; Miloslavich and others, 2024).

4. Social components

With respect to addressing the social elements of sustainable development, two areas are considered below: (a) the conditions of seafarers (including issues of gender and equity) and the broader impacts of the shipping sector on the people who work in it; and (b) the social and human impacts of the shipping sector.

Seafarers

The shipping industry as a whole is facing challenges with respect to the recruitment and retention of seafarers (Caesar, 2024). As the shipping industry is predicted to grow, the increasing shortage of seafarers will pose even more challenges in the future (Drewry, 2024). It is recognized that shipping is a high-risk occupation with a high incidence of accidents, morbidity and mortality (Slišković, 2015). Despite the fact that mariners' relationship with the sea is important for their identity (Glithero and others, 2024), the physical work environment is also demanding (Oldenburg and others, 2010). Furthermore, the often harsh operational environments are unpredictable and add more challenges to the work (Ventikos and others, 2018; see also subsect. 5B, chap. 7). Elements of the psychosocial aspects of work have been given more attention through identification of challenges such as isolation, extended time away from family and friends, bullying, sexism, stress and fatigue, all of which have a negative impact on the on-board work environment (Jepsen and others, 2017; Jonglertmontree and others, 2022; Österman and Boström, 2022; Toygar and others, 2023). These are important issues to address to make shipping a more attractive career choice.

There is evidence that seafarers can be treated unfairly. One such example is when seafarers serve on vessels under flags of convenience. The International Transport Workers' Federation (ITF) has found that such crews experience substandard working conditions and low wages and are forced to work under poor safety conditions (Christodoulou-Varotsi, 2012; ITF, 2024; see also subsect. 5B, chap. 5). Over the years, various initiatives have been taken to secure social sustainability in the shipping industry to improve conditions for seafarers. The Maritime Labour Convention, 2006, was thus adopted with the aim of ensuring that seafarers have decent working conditions and job security (ILO, 2006). In addition, IMO and the European Maritime Safety Agency (EMSA) have recognized the challenges that seafarers face, and regard the human element, that is, the complex interplay between people and the systems they work within, as a key element in addressing the social, equity and equality issues related to employment within the industry (IMO, 2006; EMSA, 2023). The Special Rapporteur on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes has called for a human-rights-based approach to this sector by States and businesses (see A/79/163).

Other interested organizations have identified the importance of well-being and psychological safety of crew on board. The Oil Companies International Marine Forum (OCIMF) performs inspections on board tanker vessels to address concerns about substandard operational practices (OCIMF, 2024). OCIMF inspections have included not only technologies but also human factors and various aspects of the work environment of the crew (OCIMF, 2021).

The shipping industry is facing technological developments that will prove to be disruptive, causing changes to the sociotechnical system. As digitalization and automation are introduced, the way work is done and will be done will further change (Mallam and others, 2020). In preparation for a future with highly automated and autonomous operation of ships, IMO has conducted regulatory scoping exercises relating to ships with various levels of automation (IMO, 2024c). New concepts of operations will require significant modifications to the International Convention for the Safety of Life at Sea, 1974 (IMO, 2024b) and the International Convention on the Standards of Training, Certification and Watchkeeping for Seafarers (IMO, 2017), and will need to address safe work practices and identify the future competencies required by mariners. Current maritime education and training has been scrutinized for such gaps in the knowledge needed to adequately prepare future navigational officers and marine engineers for roles on automated and remotely controlled vessels (Jurdzinski, 2020; Wang and others, 2020; Lokuketagoda and others, 2023). Fortunately, the disruptions arising from increased levels of automation should create new opportunities for recruitment and retention of newly trained operators and mariners and should address social inequities in employment in a traditionally male-dominated industry.

Human rights, gender and equity

The maritime sector traditionally has been characterized as male-dominated. Women represent only 1.28% of the worldwide number of seafarers certified under the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers to work as captains, deck officers, chief engineers, engine officers or radio officers (Baltic and International Maritime Council (BIMCO) and International Chamber of Shipping (ICS), 2021; see also subsect. 5B, chap. 6). The majority of women seafarers work in non-technical and non-operational sections such as catering and hotel sections

on cruise ships and ferries, to which they are stereotypically considered to be more suited (Kitada, 2022). The same trend is observed among women working in ports and shore-based maritime industries, although there are significant variation across countries and regions and between public or private ownership structures (World Maritime University (WMU), 2019; IMO and Women's International Shipping and Trading Association (WISTA), 2021; Kitada, 2022; UNCTAD, 2023).

Impacts on human health

Atmospheric ship emissions such as sulfur and nitrogen oxides, despite occurring over water, undergo chemical changes in the atmosphere and are transported over land (see figure II), where they can have deleterious effects on human health (Corbett and others, 2007; Winebrake and others, 2009). The social impacts of these effects range from work and school days missed to loss of life due to respiratory ailments or other negative health impacts. In addition, as emissions from port activities tend to occur in areas that are heavily populated, often with lower-income populations, issues of environmental justice and equity are also a concern.

Due to the human health and environmental concerns related to sulfur emissions, IMO implemented new low-sulfur fuel standards in 2020 (IMO, 2020b). These standards limit the sulfur content of fuels to 0.5% outside of emission control areas and to 0.1% within emission control areas. New low-sulfur fuels and scrubbers are now being used to achieve these low-sulfur emissions goals. The new regulations are expected to have significant beneficial impacts on human health (Sofiev and others, 2018); however, unintended trade-offs also exist. By reducing sulfur particles in the atmosphere, the use of low-sulfur fuels indirectly increases global warming (compared with high-sulfur fuels) due to radiative forcing effects (Yuan and others, 2024). Moreover, scrubber technology involves the discharge of effluent into the marine environment that includes toxic contaminants (Hassellöv and others, 2020).

Sector-relevant governance

The United Nations Convention on the Law of the Sea serves as a constitutive legal framework that addresses all issues relating to the ocean (Koh, 1982), as complemented by previously existing and subsequently developed legal instruments and customary international law, as well as a wide range of non-legally-binding instruments (see sect. 3). The development and implementation of laws and regulations on international shipping within this framework are also influenced by laws and regulations on the marine environment, fisheries, biological diversity, climate change, human rights, marine science and technology, and global political initiatives including the Sustainable Development Goals. In addressing the triple planetary crisis, shipping laws and regulations will evolve alongside other legal instruments, such as the United Nations Framework Convention on Climate Change (1994) and the Paris Agreement (2015), the Convention on Biological Diversity (and the Kunming-Montreal Global Biodiversity Framework, 2022) and the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (United Nations, 2023).

IMO is the specialized agency within the United Nations system with the global mandate to establish rules and standards for international shipping on the safety, security and protection of the marine environment (IMO, 2014). Special rules and standards have also been adopted by States and regional organizations for certain types of ships and specific regions. Under the auspices of IMO, States have adopted 59 legally binding conventions and nearly 1,000 non-mandatory codes, guidelines and recommendations that they have carefully implemented (2025 Status of IMO Treaties). There are eight major conventions with protocols and amendments that directly address the issue of marine pollution from ships. The present part of the chapter provides an overview of major developments at IMO regarding environmental regulations on shipping between 2019 and 2024.

MARPOL is the main international convention covering the prevention of pollution by ships from operational and accidental causes. It contains six annexes, targeting pollution from oil, noxious liquid substances in bulk, harmful substances carried in packaged form, sewage, garbage and air pollution, respectively (see part 2 above). Recent amendments have been focused on reducing sulfur content in fuel oil to 0.50% m/m (mass by mass) globally (MEPC, 2018b), prohibiting the use and carriage of heavy fuel oil for use as fuel by ships in Arctic waters (MEPC, 2021b) and permitting the establishment of regional reception facilities within Arctic waters (MEPC, 2022b, 2022c). In addition, new emission control areas, covering nitrogen oxides, sulfur oxides and particulate matter, have been designated for the Mediterranean Sea (MEPC, 2023a), the Canadian Arctic and the Norwegian Sea (MEPC, 2024a).

To combat greenhouse gas emissions, annex VI to MARPOL has been updated with goal-based technical and operational measures such as the Energy Efficiency Design Index, the Energy Efficiency Existing Ship Index, the Ship Energy Efficiency Management Plan, the data-collection system and the carbon intensity indicator rating for ships (IMO, 2024a). In 2023, IMO adopted an updated greenhouse gas strategy (MEPC, 2023d) with new indicative checkpoints for reaching net-zero greenhouse gas emissions by or around 2050. They are targeted for entry into force by 2027, and discussions are continuing regarding the potential adoption of a basket of midterm measures comprising both a technical element (a goal-based marine fuel standard regulating the phased reduction of the marine fuel's greenhouse gas intensity) and an economic element (based on a maritime greenhouse gas emissions pricing mechanism) following a comprehensive impact assessment process (MEPC, 2023d, 2024b (and related document in the introduction of the report); MEPC, 2024c). Further developments include the adoption of guidelines on the life-cycle greenhouse gas intensity of marine fuels and discussions on the development of an IMO life-cycle assessment framework and the terms for conducting the fifth IMO greenhouse gas study (MEPC, 2024c).

The International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004, entered into force in 2017. It is supplemented by the Code for Approval of Ballast Water Management Systems and amendments relating to the official forms for the International Ballast Water Management Certificate and the Ballast Water Record Book and the use of electronic record books. Under the Convention, there are over 70 type-approved ballast water management systems to prevent harmful organisms from spreading through ballast water (MEPC, 2018a). To further address the issue of invasive aquatic species, IMO adopted Guidelines for the Control and Management of Ships' Biofouling to minimize their transfer into new marine environments (MEPC, 2023e). Concerning the prohibition of the use of harmful anti-fouling coatings on ships, IMO has continued to develop and update guidelines under the International Convention on the Control of Harmful Anti-fouling Systems on Ships, including controls on cybutryne (MEPC, 2021c).

The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (Hong Kong Convention), which entered into force at the global level on 26 June 2025, regulates all issues around ship recycling, including the handling of environmentally hazardous substances such as asbestos, heavy metals, hydrocarbons, ozone-depleting substances and others. It also addresses concerns about working and environmental conditions in ship recycling facilities.

IMO has adopted and implemented strategies to reduce plastic litter from ships (MEPC, 2021d) and has approved recommendations for the carriage of plastic pellets by sea in freight containers (MEPC, 2024d), which address packaging, transport information and stowage of plastic pellets. The topic of plastic litter has also been under consideration by States in the context of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and the 1996 Protocol thereto concerning marine litter and microplastics, and the end-of-life management of fibre-reinforced plastic vessels and alternatives to at-sea disposal.

In order to address underwater noise, IMO adopted the revised Guidelines for the Reduction of Underwater Radiated Noise from Shipping to Address Adverse Impacts on Marine Life (MEPC, 2023c) and approved an action plan for the reduction of underwater noise from commercial shipping and guidance on the experience-building phase to address barriers to the uptake and implementation of the revised Guidelines (MEPC, 2024c).

Between 2019 and 2024, all major IMO environmental conventions gained additional ratifications. The largest increase in Parties was to the Ballast Water Management Convention (18), followed by the Anti-fouling Systems Convention (17), the Hong Kong Convention (17) and annex VI to MARPOL (16). The effectiveness of international shipping regulations depends on the ability of States to fulfil their obligations as required by the instruments to which they are Parties. The current legal framework relies heavily on flag State implementation, supplemented by port State control and limited coastal State enforcement measures. IMO has adopted unified procedures to guide port State control inspections (IMO, 2024e) and collaborates with 10 port State control regimes operating globally (IMO, 2024e). In addition, IMO has developed various mechanisms to assist IMO member States to improve their capabilities and overall performance to fully comply with IMO instruments, including, since 2016, a mandatory IMO member State audit scheme (IMO, 2013a, 2013b). As of October 2024, 92 of 176 IMO member States and three associate members have been audited (IMO, 2024d), and an annual report has been issued summarizing best practices to enhance implementation (IMO, 2024b). Between 2016

and 2022, the IMO secretariat issued five anonymous consolidated audit summary reports on a periodic basis containing lessons learned from the audits. The analysis and lessons contained in the consolidated audit summary reports are reviewed by the relevant committees and fed back into the regulatory process of IMO to help to make measurable improvements in the effectiveness of the international regulatory framework for shipping.

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Chapter 7
Mineral resources

Key points

- **Pressures**

  Marine mineral resources have been explored and exploited in maritime areas within national jurisdiction, driven by demand. Deep-sea mineral exploration has occurred both within and beyond national jurisdiction, but commercial exploitation has yet to begin. Marine mining technologies are evolving rapidly due to growing commercial interest in metal extraction, driven by the global energy transition towards net-zero emissions.

- **Impacts**

  Environmental impact assessments for commercial and project-specific mineral extraction have been conducted for offshore diamonds, phosphorites and a polymetallic sulfide deposit, but only limited studies have been conducted for polymetallic nodules or ferromanganese crusts. Environmental impact assessments are closely linked to the design and modus operandi of evolving mining technologies and the scientific and technical standards and practices adopted by States in areas within national jurisdiction and by the international community as a whole in areas beyond national jurisdiction (the Area).

- **Socioeconomic considerations**

  Depending on economic feasibility, marine mineral resources have the potential to complement mineral resources extracted from land. When mineral resources from both the ocean and the land are developed or used together, this combined activity could have an impact on the international market value of both types of resources and affect the land and marine environments. Under the United Nations Convention on the Law of the Sea, States have international legal and economic rights and obligations relating to technology transfer, cooperation and revenue distribution arising from marine mineral resources exploitation in the Area.

- **Governance and sustainability**

  Governance of maritime areas within and beyond national jurisdiction comprise various legal regimes and scientific and technical standards and practices, which create a need for international agreement and consensus. The sustainable exploration and potential exploitation of marine mineral resources depend on scientific and technological innovation, stakeholder participation, environmental management and monitoring, and reliable data for effectively assessing social, economic and environmental impacts.

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1. Introduction

The present chapter highlights developments further to chapter 23 of the first *World Ocean Assessment* (United Nations, 2017) on offshore mining industries, and chapter 18 of the second *World Ocean Assessment* (United Nations, 2021) on changes in seabed mining. It provides updates on the distribution of mineral resources and projected demand for them. It examines environmental and technological issues relating to ocean mineral exploration and exploitation. It continues with parts relating to sustainable development, including socioeconomic aspects, and concludes with a part on governance in the Area and marine regions within national jurisdiction.

The need for a comprehensive international legal framework for the oceans arose from the desire to ensure marine mineral resources for the benefit of all humanity. That concept goes back to 1 November 1967, when the Ambassador of Malta to the United Nations, Arvid Pardo, delivered a speech at the General Assembly in which he proposed that the seabed and subsoil outside national jurisdictions could be considered as *res communis omnium* and the "common heritage of humankind". His idea was reflected in Assembly resolution 2340 of 18 December 1967, by which the Assembly established an Ad Hoc Committee to Study the Peaceful Uses of the Sea-Bed and the Ocean Floor beyond the Limits of National Jurisdiction and, at a later stage, was incorporated in Assembly resolution 2749 (XXV), the Declaration of Principles Governing the Sea-Bed and the Ocean Floor, and the Subsoil Thereof, beyond the Limits of National Jurisdiction.

With the subsequent resolution, 2750 (XXV), the General Assembly decided to convene the Third United Nations Conference on the Law of the Sea, which was held from 1973 to 1982. The United Nations Convention on the Law of the Sea was opened for signature at Montego Bay, Jamaica, on 10 December 1982. It entered into force on 14 November 1994 and is presently in force for 171 Parties. The Convention and the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, adopted on 28 July 1994, establish the international legal framework for the rights and responsibilities of States with respect to, inter alia, the exploration and exploitation of ocean mineral resources within and beyond regions under national jurisdiction.

The International Seabed Authority (ISA) has developed regulations for the exploration of polymetallic nodules, polymetallic sulfides and cobalt-rich ferromanganese crusts. These three international regulations may be useful starting points for the discussion and design of national regulations for area-based management tools such as regional environmental management plans and reserved areas, which may become integral components of international and national ocean management programmes (International Seabed Authority, 2024).

2. Current status and pressures

The present part of the chapter contains a review of the current status of mineral exploration and the pressures and impacts posed by past, present and future demand for world minerals, highlighting increasing demand and evolving market trends associated with the pursuit of net-zero emissions.

Sand and gravel

Sand and gravel resources are essential for producing building materials such as concrete, as well as for beach nourishment and coastal land reclamation. By volume, sand and gravel are the most extracted marine mineral resource. Annually, between 4 billion and 8 billion tons of marine sand and sediments are dredged or mined (United Nations Environment Programme, 2023), and their associated environmental impacts, such as increasing erosion, the potential for reduced protection from storm surges and other extreme events, and damaging habitats for microorganisms that are the basis of marine food webs, have also been analysed (United Nations Environment Programme, 2022).

Marine sand and gravel are dredged on most coastlines around the world, with the exception of a few regions such as Antarctica and much of the west coast of South America. Production rates in some States, such as China, the Kingdom of the Netherlands, the United Kingdom of Great Britain and Northern Ireland and the United States of America, have remained relatively stable, while States such as India, Indonesia, the Philippines and the United Arab Emirates saw growth in production over the period from 2012 to 2022. A few countries, such as Argentina, Brazil, Japan and Saudi Arabia, have reportedly reduced

their production (United Nations Environment Programme: GRID Geneva, 2024a and 2024b).

Alluvial and placer deposits

Alluvial deposits commonly contain tin, iron minerals, gold and diamonds. A description of chromite, garnet, platinum and other platinum-group minerals and amber is provided in Andreev and others (2008). An overview of placer deposits, formed by the concentration by gravity of heavy detrital minerals transported by rivers or ocean currents, is provided in Garnett and Bassett (2005). Tin is a critical mineral used in industrial alloying applications including bronze and solder. Alluvial tin deposits are most widely documented in Indonesia, but are also found in Malaysia, Myanmar and Thailand (Kamilli and others, 2018). A global review of tin resources and reserves by the International Tin Association shows that the majority of tin reserves in Indonesia, representing nearly 7% of globally reported mining inventory, are located offshore (International Tin Association, 2020).

The potential for iron deposits occurs in several marine regions, including the Black Sea and the coastal areas of Fiji, Indonesia, Japan, New Zealand and the Philippines. Titanomagnetite iron sand deposits on the west coast of North Island, New Zealand, are some of the world's largest. Among them, the Taranaki iron-sands deposit contains an estimated 3.2 billion tons of vanadium-rich titanomagnetite iron-sand resources, making it one of the largest vanadium deposits identified globally.

Marine deposits of alluvial gold are known to occur wherever rivers carrying gold grains enter the sea. The historical deposit of Nome, Alaska, in the United States is currently being exploited alongside its associated riverine alluvial deposits (Nelson and Hopkins, 1972). Other notable examples include the historically mined beach and likely offshore placer deposits in Tierra del Fuego (De Dios Serra and others, 2026).

The best-known marine diamond deposits are located off the coasts of Namibia and South Africa, where operations began in the 1960s and were consolidated as the company Debmarine in 2002. South Africa issued its first marine diamond mining concessions in 1994 and has since continued to license active miners such as De Beers, Alexkor, Trans Hex, Bluewater Diamonds, Nautical Diamonds and Poseidon Marine. Production steadily increased until at least 2019, using vessels that ranged from artisanal vessels, where divers use handheld suction hoses, to large factory vessels (Schneider, 2020; Gales, 2024a).

Mineral precipitate deposits

Precipitates in the present review include polymetallic nodules, ferromanganese crusts and phosphorites.

Polymetallic nodules contain various metals, with the composition of those nodules differing among marine environments. Manganese and iron are the most abundant, while nickel, copper, cobalt, molybdenum, titanium and rare earth elements can also be present in significant amounts. These metals are used in a wide range of industrial applications including steel alloys, battery formulations and medical applications.

Recent developments have been focused primarily on three regions of the Area, namely, the Clarion-Clipperton Zone, the Central Indian Ocean Basin and the North-West Pacific basin (International Seabed Authority, 2024j), and three areas within national jurisdiction, namely, the Cook Islands and Minamitorishima (Japan), both in water depths over 4,000 m, and the Gulf of Bothnia (Sweden and Finland), at relatively shallow depths (~20–120 m). The first integrated test mining exercise since the late 1970s was conducted by The Metals Company and its partner Allseas in late 2022 in the Clarion-Clipperton Zone (The Metals Company, 2022).

Ferromanganese crusts broadly speaking contain the same metals as polymetallic nodules but can have high concentrations of metals such as cobalt and platinum-group elements. Hydrogenetic crusts that form on seamounts are the best studied (International Seabed Authority, 2008b), but crusts can also form on sediments and diagenetically (RSC Mining and Mineral Exploration, 2023). Crusts have been identified from the Area, in the north-western Pacific and the Rio Grande Rise (International Seabed Authority, 2026b), as well as from areas within national jurisdiction, such as those of the Cook Islands, Minamitorishima and Norway (Norwegian Offshore Directorate, 2023). Both China and Japan have recently developed seabed drilling systems to prospect for mineral resources and to perform mining tests within and beyond their respective national jurisdictions (Japan Oil Gas and Metals National Corporation, 2020; Ren and others, 2021; Xie and others, 2022).

Marine phosphorite sediments contain potentially economic levels of phosphate, which is used mostly in fertilizer and other chemical applications. The largest terrestrial deposits of phosphate are fossil uplifted marine deposits (U.S. Geological Survey, 2024). While global demand for and production of phosphates are increasing, so are efforts to use the material more efficiently (see,

e.g., Cordell and Neset, 2013), with reduction in growth rates of phosphates (FAO, 2019).

The three currently most advanced projects involving exploitation are within the national jurisdictions of Mexico, Namibia and New Zealand (Kudrass and others, 2017). While all three phosphate deposits are interpreted to have formed from authigenic processes, they vary in water depth (from tens to hundreds of metres of depth), grain size (from sand to gravel) and resource size (from tens to hundreds of millions of tons). In all three projects, it is planned to recover the phosphorites with a trailing suction hopper dredger and enriched by on-board size screening (e.g. Golder Associates (NZ) Limited, 2014). These three projects stalled at the stage of environmental impact assessment and permit approval (Environmental Protection Authority, 2015; Namibian Marine Phosphate, 2016; Odyssey Marine Exploration, 2018). The respective developers are currently exploring alternative options to advance their projects (Namibian Marine Phosphate, 2022; Chatham Rock Phosphate, 2024; Odyssey Marine Exploration, 2024).

Hydrothermal deposits

Volcanogenic polymetallic sulfide deposits are formed by the precipitation of sulfide minerals from metals dissolved in hot water that circulates through rocks. These types of deposits are known to occur throughout the geological record (Shanks and Thurston, 2012), with offshore deposits known mostly from active tectonic settings associated with spreading centres and volcanic arcs (Hannington, 2014) both within and beyond national jurisdiction. The metal content varies and may include copper, gold, zinc and lead. Active hydrothermal systems can be important hotspots for marine life and food webs supported by chemosynthetic microbes (Van Dover and others, 2020).

Recent developments regarding the exploration of these deposits include drilling and the development of new mining technologies (Bauer Group, 2021) tested in situ, notably in Japan and Papua New Guinea (Washburn and others, 2023; Alberts, 2024). Norway is preparing to issue mining licences for sulfides and manganese crusts in areas within its national jurisdiction in the first half of 2025 with a view to starting commercial exploitation in 2030.

Sediment-hosted brines were discovered in the 1960s. The zinc-rich Atlantis II, Discovery, Valdivia and Wadi Wando deposits in the Red Sea and along the border between the Sudan and Saudi Arabia are the largest known marine hydrothermal ore deposits and the only known modern analogue of brine pool-type metal deposition (Bertram and others, 2011; Laurila and others, 2015).

Biogenic deposits

The presentation below includes rare earth element deposits but excludes natural gas hydrates.

Rare earth elements (as well as scandium and yttrium) are used in a wide range of applications, including electronics. Clays rich in rare earth elements are found in various parts of the Pacific Ocean (Kato and others, 2011; Azami and others, 2018; Pak and others, 2018). Rare earth elements are found in both ferromanganese precipitates and, more significantly, in biogenic fluorapatite. In addition to deposits found in the Area, muds rich in rare earth elements have been identified in areas within the national jurisdictions of the Cook Islands and Japan.

Under the second Cross-ministerial Strategic Innovation Promotion Program, led by the Cabinet Office of Japan, a mud-lifting test was conducted off the coast of Ibaraki in 2022 using the deep-sea scientific drilling vessel Chikyū, owned by the Japan Agency for Marine-Earth Science and Technology. The Program has been under way around Minamitorishima island as the third Cross-ministerial Strategic Innovation Promotion Program since 2023. A characteristic of the red clay ooze rich in rare earth elements found in both Minamitorishima and the Cook Islands is that it can be very sticky. Testing by the Strategic Innovation Promotion Program involves the use of a piston corer and mining system.

Past demand for minerals

The period from 1900 to 1929 was considered an era of strong growth in demand. The driver was the rapid urbanization of the United States and western Europe. The initial impetus came from farm mechanization, which created a push-and-pull mechanism that contributed to urbanization. The period from 1929 to 1938, however, was an era of low growth in demand. In that decade, the United States and western Europe were in the grip of the Great Depression. The period from 1950 to 1975 experienced a return to high growth in demand with the post-war economic boom. The period from 1975 to 2000 was an era of weaker growth in demand after the post-war boom, and it came to an end by the mid-1970s amid widespread industrial strife and persistent inflation. Thereafter, a boom in demand for metals from emerging

economies, led by mining in China, began in the late 1990s and early 2000s (Lynch, 2024).

Rising demand for minerals

According to the *Global Resources Outlook 2019*, metals extraction increased 3.5 times between 1970 and 2017 (IRP, 2019). Global domestic extraction of metal ores is projected to grow at a yearly average of 1.7% from 2015 to 2060. It is also projected that 9% of total global resources extraction will be of metal ores in 2060.

Depending on their economic feasibility, deep-seabed minerals could play a role in securing a sustainable supply of metals (Hernandez, 2023). Mineral deposits on the seabed tend to contain higher metal content than those on land (Heffernan, 2019). World demand for minerals may be difficult to predict, but it will certainly be influenced by three general factors: (a) increasing use of mineral commodities; (b) demographic increase; and (c) economic growth.

Under certain scenarios, variations in economic growth might affect future mineral demand more than demographic increase alone. Per capita consumption of a high number of minerals has risen globally during the past decade, and the greatest increases have been related to economic growth (Briskey and Schulz, 2007; Kesler, 2007).

Future mineral demand, including of critical minerals (International Energy Agency, 2024), in support of the green energy transition will be very high in 2040 and 2050. Due to this predicted increase in demand, a potential risk of imbalances in supply and demand is possible. For instance, copper is required for all power generation and transport technologies. Lithium, cobalt and graphite are used in electric car batteries, as is nickel, which is also used in a number of power generation technologies. Rare earth minerals are needed for offshore wind turbines. Nickel and platinum-group metals are important for hydrogen production, and rare earth elements play a role in hydrogen production, as well as in wind turbines and batteries. Aluminium also plays an important role across a wide range of green technologies (United Nations Environment Programme, 2024).

Market trends

A 2020 World Bank report on minerals for climate action found that production of metals could increase by nearly 500% by 2050 (Hund and others, 2023). The potential global market for deep-sea mining driven by the demand for critical minerals is projected to expand from $650 million in 2020 to $15.3 billion by 2030 (Global Mining Review, 2021).

Global mine production of rare earth elements, which are essential for manufacturing technological products, is estimated to have increased to about 350,000 tons of rare earth oxide equivalent. Such production will have a transversal impact on the economy's primary, secondary and tertiary sectors (Cuadros-Muñoz and others, 2024).

The Ministry of Industry and Information Technology of China raised 2023 quotas to 240,000 tons for rare earth mining and separation and to 230,000 tons of rare earth oxide equivalent. In 2023, mine production quotas of rare earth were set at 220,850 tons for light rare earths and 19,150 tons for ion-adsorption clays (U.S. Geological Survey, 2024).

Towards net-zero emissions

According to the *World Energy Outlook 2022*, mineral requirements for green energy technologies will quadruple by 2030 in the net-zero emission scenario, with particularly high growth in materials for electric vehicles (International Energy Agency, 2022). The type of mineral resource required varies by technology. Lithium, nickel, cobalt, manganese and graphite are crucial for battery performance. Rare earth elements are essential for permanent magnets in wind turbines and electric vehicle motors. Electricity networks require large amounts of copper and aluminium, with copper a cornerstone of all electricity-related technologies.

According to the World Energy Outlook special report *The Role of Critical Minerals in Clean Energy Transitions*, revised in 2022, the collective demand for critical metals is expected to increase almost twentyfold between 2020 and 2050, from less than 10 million tons to roughly 150 million tons, to meet the demand for low-carbon energy technology under the net-zero emission scenario (International Energy Agency, 2021). Critical minerals and metals required for battery storage are anticipated to increase nearly fortyfold, while those required for low-carbon electric power generation are expected to triple. The total market size of critical minerals and metals such as copper, cobalt, manganese and various rare earth metals will grow almost sevenfold between 2020 and 2030 in the net-zero pathway. One of the most recent assessments of critical minerals involves scenario forecasts for recycling (International Energy Agency, 2025), and, in some cases, growth in primary demand for critical

minerals may stabilize or even drop by 2035, although total required inventory will continue to grow into the next few decades.

The global infrastructure financing gap is estimated to be around $15 trillion by 2040. In order for everyone in the world to have basic infrastructure over the next 20 years, the world would need to increase its annual infrastructure spending by just under $1 trillion every year, compared with the previous year's spending. The *Global Material Resources Outlook to 2060* issued by the Organisation for Economic Co-operation and Development estimates that the greatest increase in resource consumption by 2060 will be in minerals, especially construction materials and metals, particularly in fast-growing economies (OECD, 2019). According to the National Mining Association of the United States of America, the United States Department of Defense alone uses nearly 750,000 tons of minerals each year (National Mining Association, 2017).

3. Impacts

The present part of the chapter contains a review of potential environmental impacts and technological developments relating to the exploration for and exploitation of ocean mineral resources and describes the need to achieve a balance among them. This is crucial in order to ensure that if and when exploration and/or exploitation takes place, the social and economic needs of present and future human generations are addressed.

Environmental issues

The question of whether environmental impacts from proposed deep-sea mineral extraction are acceptable is currently still largely unanswered for many seabed mineral types. Environmental impact assessments for the exploitation of marine mineral resources at a commercial scale have been carried out only for offshore diamonds (Debmarine Namibia, 2024), phosphorites (Chatham Rock Phosphate Limited, 2014) and a single polymetallic sulfide deposit, for example, at the Solwara 1 project (Nautilus Minerals Niugini Limited, 2008). No environmental impact assessments have been completed for polymetallic nodules or ferromanganese crusts. Limited environmental impact assessments have been completed to support pilot testing of nodule mining equipment (Global Sea Mineral Resources, 2018; BGR, 2019; Sharma and Goswami, 2021).

Good-practice environmental impact assessments follow a structured approach (Clark and others, 2017; Clark and others, 2020). They usually start with a scoping exercise, proceed to the collection and compilation of baseline data and then culminate in the project-specific environmental impact assessment, which is used to justify an environmental permit (or, for example, an exploitation contract with the ISA). Environmental impact statements might be required for exploration and pilot mining tests before the project environmental impact assessment is carried out. A project environmental impact assessment or statement will usually include a description of the types and scope of activities contemplated, an environmental risk assessment of those activities (usually done in line with a framework such as DPSIR (drivers, pressures, state, impact, response) (Maxim and others, 2009; Elliott and others, 2017) and the incorporation of peer and public review stages.

It is important to note that a pre-feasibility or feasibility study is normally needed for a detailed description of activities (see subpart below on technological issues). That study would then need to be aligned with the environmental impact assessment.

The environmental impact assessment is usually part of a broader framework, called an ecosystem-based management framework (see, e.g., United Nations Environment Programme, 2025). This widely recognized practice integrates various environmental programmes to assess risk, organize knowledge, inform stakeholders, direct monitoring requirements and activities, and ultimately maintain a healthy ecosystem. In addition to the environmental impact assessment process, other parts of an ecosystem-based management framework may include:

- A regulatory regime, including overarching principles and more detailed requirements and recommendations within standards and guidelines, such as the Mining Code of ISA (International Seabed Authority, 2026c).
- Baseline data sets (from marine scientific researchers and other developers).
- Related cases from other developers and mining tests.
- Regional assessments, such as strategic environmental assessments (SPREP, 2020) and regional environmental management plans, including

consideration of cumulative impacts (International Seabed Authority, 2022d).

- Stakeholder engagement aspects, including independent review by subject-matter experts and public involvement.

The current state of knowledge regarding seabed mineral districts and projects is considered within the ecosystem-based management framework. For example, contributions to understanding baseline conditions and possible environmental impacts may begin broadly and generically, then become more focused as specific projects approach the permit application stage. Through constructive dialogue with stakeholders, issues are addressed and flaws can be recognized at an early stage.

Currently there is considerable focus on the possible exploitation of polymetallic nodules in areas beyond national jurisdiction, where several advanced projects are undergoing environmental impact assessments (International Finance Corporation, 2013). A key issue is that regulations for exploitation have not yet been finalized by the regulator, ISA. In addition, important work is still needed to inform supporting standards and guidelines. Some current initiatives include the following (International Seabed Authority, 2024c):

- Methodological work for biodiversity assessment, as part of an action plan for marine scientific research.
- Development of environmental threshold values (including those related to generated plumes and noise).
- Interactions between fishing and activities related to mineral resources.
- Biogeochemical modelling, to better understand carbon storage and release in the deep sea (Ocean-ICU, 2023).
- Internalization of environmental costs.
- An intersessional expert group, formed by ISA, on the development of binding environmental thresholds on (a) toxicity; (b) turbidity and settling of resuspended sediments; and (c) underwater noise and light pollution.

Technological issues

Any sustained development of seabed minerals depends on cost-effective technologies. Particular risks arise when novel technology is used.

While, in theory, technology can be developed (see, e.g., European Marine Energy Centre, 2008) independently from projects (see, e.g., McCarthy, 2015), in practice the two are often intertwined. Scoping studies and subsequent pre-feasibility studies usually consider alternative technological options that may be at different levels of technology readiness. Even though seabed minerals originate from the ocean, their onshore processing involves the same challenges as in land-based mineral processing (McNulty, 1998).

In the previous century, significant efforts were made with respect to exploration and mining tests, although interest subsided after the 1970s (Lipton and others, 2016). Recently, the interest in the extraction of polymetallic nodules has been rekindled. The United Nations and, later, ISA have organized technology-focused workshops approximately once per decade since the 1970s (United Nations Ocean Economics and Technology Branch, 1984; Office of Resources and Environmental Monitoring, 1999; International Seabed Authority, 2008a). After issuing preliminary economic assessments in 2015 (Golder Associates, 2015) and 2019 (AMC Consultants, 2019), Nauru Ocean Resources Inc. and its parent, The Metals Company, plan to issue pre-feasibility studies in 2025 for both mining and metallurgical processing (The Metals Company, 2023, 2025).

The entire value chain, from seabed exploration and exploitation to product sales, requires some level of development. Additional effort is being focused on reducing environmental impacts, including through the refinement of available technology (Rizea and others, 2023; NOV, 2026) and the development of new technologies (see, e.g., Beijing Pioneer Hi-Tech Development Corporation Ltd., 2024). Other areas of technological development include:

- Environmental monitoring systems (JPI Oceans, 2023; Silva and others, 2023).
- Adaptation of existing ships (OE Staff, 2022).
- Alternative lift system development (NOV, 2026).
- Alternative nodule collection techniques (Impossible Metals, 2023; Ocean Mining Intel, 2023).
- "Ship-to-shore" programmes, including class and safety considerations (Gales, 2024a), and the forthcoming ship-to-shore joint industry programme.
- Metallurgical programmes (The Metals Company, 2023).

Technological developments are also continuing for other types of deep-sea minerals. Below are a few examples.

- One focus of technology development for seafloor massive sulfide mining is to reduce environmental impacts, including plumes (Bauer Group, 2021).
- Research is ongoing on cutting ferromanganese crusts, as variable crust thickness makes it challenging to achieve consistent cuts at sufficient production rates (JOGMEC, 2020; Xie and others, 2022).
- Research is being carried out to improve liquefaction for the lifting of muds rich in rare earth elements (JAMSTEC, 2023).

Apart from the technological issues related to the start of production, longer-term consideration needs to be given to the scale of production. Future possible economies of scale should ideally be factored into seabed mineral exploitation permits. Production rates should also be considered in both environmental impact assessments and cumulative impact assessments. In shallow-water marine industries, some operations have progressively expanded in scale, such as De Beers' marine diamonds operations (Richardson, 2007), while others have maintained flatter production profiles, such as PT Timah's tin operations (Anderson and Oosthuizen, 2024).

4. Socioeconomic considerations

The second *World Ocean Assessment* contained an overview of the economic landscape for seabed mining and the associated social impacts. The present part of the chapter contains an update to the information provided in the second *World Ocean Assessment*. It is important to note, however, that, at present, only exploration activities are taking place in the Area. The decision on whether seabed mining may proceed to the exploitation phase rests with States Parties of the United Nations Convention on the Law of the Sea.

According to article 136 of the Convention, the Area and its resources are the "common heritage of humankind". In line with this principle, any activity in the Area should be for the benefit of all countries, with a focus on equitable sharing, particularly with developing nations. ISA has the mandate to regulate activities in the Area and to ensure that resources are exploited fairly, that international cooperation is promoted and that the environment is protected. Accordingly, economic considerations are an integral part of negotiations on exploitation regulations.

In 2015, the Council of ISA adopted seven priority deliverables for the development of the exploitation code. The second priority entailed the development of a payment mechanism for exploitation activities that follows detailed financial and economic modelling based on proposed business plans. During the following two years, various workshops were organized to develop such a payment system. In 2018, the ISA secretariat commissioned the Massachusetts Institute of Technology to develop an economic model for the exploitation of polymetallic nodules that could be used to model various payment systems and royalties (International Seabed Authority, 2023c). The Institute compared results with three other models, received from China, Germany and the Group of African States. In 2019, the Council agreed to set up an open-ended working group to discuss the financial model and, in particular, to review the comparative study. In 2020, the ISA secretariat commissioned two consultants to examine comparable land-based mining systems (CRU and RMG Consulting, 2020). In 2022, some member States suggested that the cost associated with environmental externalities should be internalized in the model. In 2023, two studies on the evaluation of natural capital were completed, which are expected to inform further policy discussions (Banfder, 2023; Brander and Guisado Gõni, 2023). Between 2019 and 2024, the open-ended working group met on 10 different occasions.

Several financial mechanisms govern how contractors contribute to the economic benefits derived from activities in the Area. While the contractor payment regime is the overall financial structure determining how contractors compensate the international community for extracting resources from the Area, there are other, non-monetary, benefits to humankind. One specific type of payment within the contractor payment regime consists of royalty payments paid to ISA for the rights to exploit nodules. Various ad valorem royalty-fee structures, including fixed, variable and staged structures, are currently under negotiation with respect to percentages (Hogan, 2008). Once commercial mining begins in the Area, the administrative costs of ISA, to be covered by ISA member State contributions, will be financed by the revenue generated from royalties. According to article 151 (10) of the Convention, another portion will flow to support the establishment of an economic assistance fund. This fund will assist developing countries when their economies are adversely impacted by deep-seabed mining, for example, through reductions in mineral prices

or decreases in export volumes. Another portion of the revenue generated from the royalties will flow to an environmental compensation fund which is intended to fill any liability gaps. The remaining revenue will be distributed among the member States, with a particular focus on developing States.

In 2022, the Group of African States assessed the various payment regime options and how they interact with the tax systems of sponsoring States. In 2023, the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development analysed various equalization measures as an addition to the payment regime options to ensure a level playing field between contractors and sponsoring States (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2023; Roth and others, 2023; Wilde, 2024). Various options were deliberated during the twenty-ninth session of ISA, in 2024 (International Seabed Authority, 2024f), and these discussions continued at Council negotiations during the thirtieth session (2025).

Benefit-sharing is a crucial element of the legal regime, as it addresses the interests and needs of developing States. In 2022, the ISA secretariat published a policy brief outlining its work on benefit-sharing, which has been under the supervision of the Finance Committee since 2018 (International Seabed Authority, 2022a). The brief draws on the findings of ISA technical study 31, which examines the concept and mechanisms for implementing benefit-sharing and also highlights non-monetary benefits (International Seabed Authority, 2022f).

Alternative approaches to benefit-sharing include the establishment of a seabed sustainability fund. The ISA Secretary-General presented a proposal for the fund's establishment to the Finance Committee in 2023, and member States have yet to discuss it (International Seabed Authority, 2023b, 2024a, 2024b). Some studies suggest, based on modelling for various distribution approaches for the 170 member States, that the economic benefit for an individual country may be limited, and also highlight the potential value of the seabed sustainability fund in supporting broader sustainability goals (Wilde and others, 2023). The draft exploitation regulations frequently reference social impacts, emphasizing that all activities in the Area should serve humankind. One key mechanism to achieve this is capacity-building, which fosters the development of human capital and creates lasting, intergenerational benefits.

Under the Convention (see arts. 144, 273 and 274), ISA has a duty to design and implement mechanisms that support capacity-building for developing States. These mechanisms promote technology transfer and expand opportunities for participation in activities in the Area. Experts trained through ISA programmes contribute by sharing their knowledge and skills with local specialists, strengthening expertise within their home countries.

A key social component is the legal obligation for contractors to provide training opportunities for personnel from developing States, notably through the contractor training programme (International Seabed Authority, n.d.a.). This programme has delivered world-class training in deep-sea research and technology development to experts from developing countries. To date, over 350 professionals have benefited, including 115 women and 118 trainees from least developed countries, landlocked developing countries and small island developing States. In 2024, a stocktaking policy brief highlighted the accelerated efforts of ISA in this domain, emphasizing the essential role of collaborative partnerships (International Seabed Authority, 2024c).

5. Legal and regulatory frameworks for activities relating to marine mineral resources

The Area

In accordance with article 1 of the Convention, "Area" means the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction. The Convention recognizes the Area and its resources as the common heritage of mankind, and provides that activities in the Area shall be conducted for the benefit of all humankind as a whole.

Activities in the Area are managed by ISA, an autonomous international organization established under the Convention and the Agreement relating to the Implementation of Part XI of the Convention (the 1994 Agreement). As at the time of writing, ISA has 172 members (comprising 171 States and the European Union) with a seat in the Assembly, the supreme organ and plenary body of the Authority. The Council, the executive body, comprises 36 members selected according to a formula that requires representation of special interests, including States with

large populations and those that are major importers or net exporters of the commodities to be derived from the Area. Council decisions may result from recommendations by its subsidiary organs: the Legal and Technical Commission and the Economic Planning Commission. As established by the 1994 Agreement, the functions of the Economic Planning Commission have been carried out by the Legal and Technical Commission. The 1994 Agreement also set the functioning of the Finance Committee, whose recommendations shall be considered by the Assembly and Council of ISA. The Finance Committee is tasked with considering the administrative and budgetary implications of proposals involving expenditure from funds of the Authority and with considering the rules, regulations and procedures on the equitable sharing of financial and other economic benefits derived from activities in the Area. As a general rule, decision-making in the organs of the Authority should be by consensus.

The Authority has adopted regulations on prospecting and exploration for polymetallic nodules, polymetallic sulfides and cobalt-rich ferromanganese crusts and is currently discussing draft regulations, standards and guidelines for the exploitation of these resources. In July 2023, following the announcement by Naoero of its intention to submit in 2025 an application for the exploitation of polymetallic nodules in the Area, the Council decided that exploitation should not commence in the absence of regulations.

The activities developed under the 31 contracts currently in place for exploration for minerals in the Area are monitored through reports submitted annually by contractors to the Authority (International Seabed Authority, 2024e).

Recent developments in areas under national jurisdiction

In the present subpart, only two jurisdictions will be considered.

Cook Islands

The development of deep-seabed minerals is viewed as a possible material contributor to diversifying the economy of the Cook Islands, and successive governments have therefore maintained an interest in the sector.

The initial Seabed Minerals Act came into force in 2013, leading to the establishment of the Seabed Minerals Authority. In 2019, the Act was repealed with the promulgation of a new one that had undergone more extensive stakeholder and public review. The Authority manages the industry in consultation with an Advisory Committee that is composed of community leaders and a technical advisory group consisting of relevant government agencies. Some aspects of due governance are managed through the interaction between legislation and institutions. The Seabed Minerals Act, the Environment Act (2003) and the Environment (Seabed Minerals Activities) Regulations 2023 are thus administered by the National Environment Service. The Marae Moana Act 2017 is administered by the Marae Moana Council, and the fishing-oriented Marine Resources Act (2005) is administered by the Ministry of Marine Resources. The entire exclusive economic zone of the Cook Islands (an area of almost 2 million km^2) is defined in law as a multiple-use marine park and includes marine protected areas (MPAs) within 50 nautical miles of each of the 15 islands (~14.8% of the exclusive economic zone). All environmental data, as well as the details of exploration licences and any approved variations, go into the public domain.

Following a competitive tender for the exploration of seabed minerals in October 2020, a total of three licences were issued to Cook Islands-based companies in February 2022. The exploration licence is valid for an initial five-year period, and a licence-holder may apply to have it renewed, subject to statutory requirements.

Norway

In July 2019, the Norwegian Seabed Minerals Act, relating to mineral activities on the continental shelf of Norway, entered into force. In January 2024, the parliament of Norway voted in favour of the Government's proposal to open up an area of approximately 281,000 km^2 for exploration of deep-sea minerals, with a particular focus on polymetallic sulfides and ferromanganese crusts. The Seabed Minerals Act stipulates that any targeted area must be subject to an opening decision by the Government, based on an impact assessment that identifies the potential effects of such an opening on the environmental, economic and social pillars of sustainable development. The impact assessment was finalized in October 2022 and followed by the receipt of consultation inputs.

The licence regime includes a non-exclusive survey licence and an exclusive extraction licence. The former is granted for a period of up to five years and covers a specific area for the exploration and mapping of minerals for commercial purposes. The latter gives the licensee the exclusive right to conduct a survey and to extract all minerals for commercial purposes in the area covered by

the licence. An extraction licence can be granted for an initial period of up to 10 years with a possibility of applying for an extension. Unlike the survey licence, the extraction licence may be granted only to Norwegian entities.

6. Sustainability pathways in the Area and regions under national jurisdiction

Sustainable development is aimed at meeting human needs without compromising future generations' ability to do the same (see A/42/427). A key aspect of sustainability under the Convention is the precautionary approach, which guides all activities in the marine environment. States and ISA are obligated to use the best available scientific data to prevent significant harm to the marine environment while promoting the responsible and sustainable use of deep-sea resources.

The sustainable exploration and potential exploitation of deep-sea minerals depend upon four key pillars: (a) scientific and technological innovation; (b) inclusive stakeholder participation; (c) environmental management; and (d) reliable data. These pillars are integral to the responsibility of ISA for overseeing activities related to deep-sea mineral resources in the Area and ensure that exploration and exploitation are conducted in a manner consistent with international law, including the precautionary approach.

Advancements in science are key to guiding sustainable development. The Convention, in article 143, highlights the mandate to conduct and promote marine scientific research in areas under national jurisdiction and in the Area. In 2017, in paragraph 292 of its resolution 72/73, the General Assembly proclaimed the United Nations Decade of Ocean Science for Sustainable Development. In support of the Decade, the Assembly of ISA adopted its Marine Scientific Research Action Plan in 2020 (ISBA/26/A/17). The plan sets out six strategic research priorities and has since served as a global framework and agenda for the advancement of deep-sea research (see ISBA/27/A/4, ISBA/28/A/8 and ISBA/29/A/5). In 2024, a stocktaking report was published that put forward recommendations for shaping the future marine research landscape (International Seabed Authority, 2024h). One recommendation, for example, is that the Authority should channel its short-term focus towards addressing knowledge gaps identified in the regional environmental management plan process in order to support the science-policy interface through projects that have contributed to a joint programme initiative.

Technological innovation plays a vital role in implementing the precautionary approach in deep-sea resource management by enhancing the ability to prevent harm to marine ecosystems. Advances in technology support the development of sophisticated monitoring and assessment tools, allowing for real-time data collection and more precise evaluations of potential environmental impacts. For example, improved remote-sensing technologies, autonomous underwater vehicles and advanced satellite systems can provide detailed insights into the health of deep-sea habitats and ecosystems. However, it is also important to consider the potential risks associated with technological advancements, such as unintended ecological impacts and ethical concerns regarding the use of artificial intelligence and automation. Significant technological advancements have been made, and, in April 2024, experts of an ISA scoping workshop identified five priority areas for future development: ocean observation and communication; monitoring; autonomy; automation, robotics, artificial intelligence and machine learning; and mining, energy and metal processing (Sharma, 2017; International Seabed Authority, 2022c, 2022e, 2024l).

Inclusive stakeholder participation is essential for ensuring transparency and accountability in the governance of marine resources. ISA actively engages a diverse range of stakeholders to support informed decision-making and strengthen its mandate. This ongoing commitment aligns with the strategic priorities of ISA, which are focused on advancing marine resource governance through collaboration and science-based policies (International Seabed Authority, 2018, 2019, n.d.b).

Environmental management is essential to sustainable development, balancing the need for resource extraction with the protection of marine ecosystems. Regional environmental management plans are designed as measures to protect the marine environment in specific parts of the Area from the potential harmful effects of activities in the Area. They are aimed at providing a framework for ensuring environmental protection while enabling the sustainable use of marine resources. Although regional environmental management plans are informed by environmental assessments, their development is not based solely on regional environmental impact assessments but also incorporates broader scientific, environmental

and regulatory considerations (International Seabed Authority, 2026a). The Legal and Technical Commission of ISA is currently advancing standardized procedures for the development and review of such management plans, which include elements such as environmental goals, management measures and monitoring processes. To support these efforts, the Commission is also creating technical guidance to complement the standardized procedure (see ISBA/29/C/10 and ISBA/29/LTC/8). One notable success is the regional environmental management plan of the Clarion-Clipperton Zone, in which a scientific review identified additional ecologically significant areas that were subsequently granted protection.

Reliable data are essential for informed decision-making and sustainable development in deep-sea mining. They underpins rigorous environmental impact assessments, supports the creation of robust regulatory frameworks and enables responsible management of deep-sea mineral extraction, thereby safeguarding fragile marine ecosystems and promoting long-term economic viability. ISA shares the non-confidential data of contractors, following the FAIR (findable, accessible, interoperable and reusable) principle. The Authority's DeepData database serves as a central repository for environmental data relating to the Area, with an average of 5,580 monthly visitors as of April 2024.[1] ISA continues to enhance data quality through partnerships with organizations such as the World Register of Marine Species (WoRMS) and the Ocean Biodiversity Information System, hosted by the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO-IOC), as well as the Natural History Museum, London, and the Pew Charitable Trusts, which have led to an in-depth assessment of the quality of biological data (Rabone and others, 2023).

1 See https://data.isa.org.jm/isa/map.



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Chapter 8
Desalination and salt production (liquid salt)

Key points

Desalination capacity is expanding rapidly to meet rising water demand

- Desalination has become a critical water supply strategy for many water-stressed regions, with global capacity continuing to grow as populations and urbanization increase.
- Many coastal States now rely on desalination to provide a substantial share of municipal and industrial water.
- Implication: as dependence increases, Governments must ensure that desalination is planned and operated in ways that do not exacerbate local environmental pressures.

Environmental impacts from brine discharge and energy use remain major concerns

- Desalination plants produce large quantities of concentrated brine that can affect marine ecosystems by altering the salinity, temperature and chemical composition of receiving waters.
- High energy demands, often reliant on fossil fuels, mean that desalination contributes to greenhouse gas emissions unless supported by renewable energy sources.
- Implication: scaling desalination sustainably requires improved discharge management and increased integration of renewable energy to reduce ecological and climate impacts.

Advances in technology offer opportunities to reduce impacts and improve efficiency

- New membrane technologies, improved brine treatment systems and hybrid renewable energy desalination models are emerging to lower environmental footprints and operational costs.
- Some countries are also exploring circular economy approaches, including mineral recovery from brine.
- Implication: investing in innovation and best practice standards can help Governments meet water security needs while reducing long-term environmental risks.

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1. Introduction

Growing need for desalination

Of the Earth's 1.4 billion km^3 of water, only 2.5% is freshwater and 0.3% readily accessible to humans (World Bank, 2013). Increasing population, urbanization, climate change and economic developments have resulted in more than 2 billion people experiencing high water stress (UN-Water, 2018). Estimates for 171 countries indicate that 31 countries experience water stress between 25% and 70%, 22 countries exceed 70% and 11 countries surpass 100% (UN-Water, 2018). By 2050, 40% of the world's population is projected to live under severe water stress (Salinas-Rodriguez and others, 2021). Oceans cover 140 million square miles (approximately 363 million km^2) of the Earth's surface and nearly 2.4 billion people live within 100 km of the coast (United Nations, 2017). To address water scarcity, saline water desalination offers promising solutions. More than 150 countries are using desalination to supply potable water to more than 300 million people (World Bank, 2019a). It is well established that unconventional water sources such as desalination will play a key role towards meeting the Sustainable Development Goal 6 targets for sustainable water management in the coming years (United Nations Environment Programme (UNEP), 2021).

Desalination systems overview

Desalinated water is used or can be used in various economic sectors such as industry, agriculture, food processing, healthcare and recreation (Al-Jabri and others, 2019). Among these, the municipal sector uses 62.3%, while industries use 30.2% of desalinated water production (Cai and others, 2023). In 2019, the desalination market was highest in the Middle East and North Africa region (45.32%), followed by East Asia and Pacific (17.52%), North America (11.34%), Western Europe (8.75%), Southern Asia (2.94%), Eastern Europe and Central Asia (2.26%) and sub-Saharan Africa (1.78%). In 2020, approximately 97.2 million m^3 per day of freshwater was produced globally from 20,971 projects, supported by 16,896 installed desalination plants (Do Thi and others, 2021).

On the technological front, the most commonly used commercial desalination methods include reverse osmosis, multi-stage flash distillation and multi-effect distillation and electrodialysis (Almasoudi and Bassam, 2024). In 2000, thermal technologies and reverse osmosis accounted for 93% of total water volume produced by the desalination process. Since then, both the number and capacity of reverse osmosis plants have risen exponentially, while thermal technologies have seen marginal increases (Jones and others, 2019). Membrane desalination technology (involving reverse osmosis) accounts for approximately 85% of total worldwide desalination plants and generates approximately 69% of global desalination capacity. Whereas thermal desalination involves multi-stage flash distillation and multi-effect distillation, providing approximately 18% and 7% of global desalination capacity, respectively. It accounts for 2.1% and 5.6% of total desalination plants, respectively (Elsaid and others, 2020a; Curto and others, 2021). In terms of intake sources, desalination plant productions involve 61% seawater, 21% brackish water, 8% rivers, 6% wastewater, 4% pure water and 1% brine (Jones and others, 2019).

Salt production and desalination brine systems

Salt is a strategic commodity and fundamental part of society that satisfies human and industrial needs. Traditionally, sea salt has been produced through natural evaporation of seawater in large and shallow basins. Worldwide, salt extraction is approximately 40% through solar evaporation[1] of seawater, 35% from inland brine and 25% from mining of rock salt and brine solutions, although global productions are fluctuating (Tridge, 2021). In 2023, global salt production was estimated to be approximately 270 million metric tons, with China, the United States of America and India being the largest producers of salt (USGS, 2024). Conveying desalination discharges to conventional salt production ponds offers an integrated approach to recovering valuable salt from brine (Cipollina and others, 2012; Wenten and others, 2017). Seawater desalination plants produce more than 150 million m^3 of brine per day globally, 80% of which is discharged within 10 km of coasts (Eyl-Mazzega and Cassignol, 2022). Brine production in Saudi Arabia, the United Arab Emirates, Kuwait and Qatar accounts for 55% of the total global share (Jones and others, 2019). Reject brine from desalination plants contains high

[1] See https://eusalt.com/about-salt/salt-production/solar-evaporation/.

total dissolved solids contents typically ranging between 55 g/L and 70 g/L (Panagopoulos, 2021a). Findings suggest that the integration of brine management with salt recovery processes can offer opportunities for salt production and recovery; however, further investigations are needed to establish these strategies.

Integration strategies for desalination, salt production and raw materials extraction

Methods commonly used for brine disposal include sea discharge, land disposal, evaporation, membrane distillation, forward osmosis, deep electrodialysis, capacitive deionization, well injection and sewage disposal (Mavukkandy and others, 2019). Disposal method selection depends upon brine quantity, quality, discharge location, the availability of dump sites and operational and transportation costs. Some 5% to 33% of total desalination cost is spent on brine disposal processes (Backer and others, 2022). Minerals recovery and waste-to-value products offer more cost-effective solutions for handling brine. Minimal liquid discharge and zero liquid discharge systems for brine treatment enhance freshwater recovery and minimize wastewater effluent. The global minimal liquid discharge and zero liquid discharge market was worth $0.71 billion in 2018 and is expected to rise to $1.76 billion by 2026, showing a 12.1% compound annual growth rate (CAGR) during the projected period (Panagopoulos, 2021a). Most modern seawater desalination plants use reverse osmosis membranes with a recovery of 30–50% water depending on the seawater salt concentration and the processes involved. Significant salt concentration increase makes recovery of sodium chloride more economical than conventional production methods (Sharkh and others, 2022). Beside sea salt extraction, brines and bitterns (ultra-concentrated brine left after the sea salt precipitation) have been assessed as an important source of critical raw materials such as boron, magnesium, rubidium and many other trace elements for which extraction technologies have been recently developed and tested at the pilot scale (Randazzo and others, 2024). Overall, data suggest that sea salt production and mineral recovery from brine can serve as a promising integration strategy for desalination plants and can be established with additional studies.

2. Pressures and impacts

While desalination systems offer reliable water supply and socioeconomic welfare, they also lead to potential negative impacts on the environment. The following picture depicts desalination impacts and potential mitigation measures:

Environmental impacts of brine discharges

Concentrated brine discharge to sea is the main waste product of desalination plants. Brine discharges from desalination plants lead to higher salinity, elevated temperatures and release of source water conditioning chemicals. The desalination wastewater salinity ranges 55 to 70 parts per thousand (ppt) compared with regular ocean salinity of 35 to 45 ppt worldwide (Voutchkov and others, 2019). Brine produced through reverse osmosis process has approximately twice the salinity of seawater, while thermal desalination processes produce brines of approximately 1.5 times seawater salinity. Brine plumes of waste dissipate rapidly, and salinity stress is often limited to organisms located directly in the vicinity of the outflow (Omerspahic and others, 2022; Panagopoulos and others, 2019). Spatial distribution of brine plume (including perimeter, flow direction and buoyancy) varies according to discharge volume, rate and dispersion technology (Petersen and others, 2018). An increase in salt concentration raises water density and turbidity and fosters stratification of receiving water (Miri and Chouikhi, 2005). Various chemicals used and produced during the desalination process end up in brine discharges. These compounds include chlorine, anti-scalants, coagulants, flocculants, strong acids or bases, oxidizing agents, reducing agents, anti-fouling agents, foaming inhibitors and heavy metals that are released into the water (Petersen and others, 2018; Do Thi and others, 2021; Omerspahic and others, 2022). These compounds have the potential to alter the pH of the water, increase the amount of nutrients and produce more algae (Do Thi and others, 2021). Overall, it is well established that brine discharge from desalination plants pose serious environmental concerns.

Impacts on marine life and source environment

Environmental impacts of desalination plants on marine life and source environment depend upon factors such as nature of feed water, desalination technology used and waste brine management (Missimer and Maliva, 2018). On the water intake side of desalination plants, marine life is affected through three main processes:

entrapment, impingement and entrainment. Entrapment involves trapping marine species in systems with long offshore pipelines and screens at the onshore end. During impingement, aquatic organisms are sucked against the intake screens and cannot escape. Entrainment occurs where smaller species pass through the intake screens and are subsequently killed during the desalination processes (Nielsen and others, 2024). The primary impact of conventional open-ocean intake systems[2] is the impingement and entrainment of marine organisms. Submerged pipelines or open intakes of desalination plants remove fish eggs and small marine organisms (such as plankton and larvae) from seawater (Missimer and Maliva, 2018; Petersen and others, 2018). Entrainment also affects membrane biofouling associated with the intake of seawater and toxins in the seawater from harmful algal blooms (Anderson and others, 2017). It is well established that desalination plant water intake structures widely impact nearby marine life.

For locations with closed or shallow circulations, sluggish currents and abundant marine life, the impact of the brine plume can be significant on the local marine ecosystem (Panagopoulos and Haralambous, 2020). The temperature rise due to brine discharges causes lowering of dissolved oxygen content in receiving waters, increases metabolism rate of its faunal inhabitants and elicits physiological and behavioural responses in organisms (Miri and Chouikhi, 2005). Concentrate disposal can locally harm benthic communities if poorly diluted discharge is allowed to flow across the marine bottom (Missimer and Maliva, 2018). Brine discharges may cause depletion of benthic community abundance and diversity (Sola and others, 2020). Brine effluent impacts coastal species (such as bacteria, zooplankton, seagrass, fish larvae and corals). Studies have suggested alteration of activity and diversity of bacteria and microalgae, reduction in meiofauna abundance and impacts on the physiology of seagrass meadows near outfall sites (Petersen and others, 2018). These processes can lead to the disruption of marine habitats and ecosystems by altering the connections between ecosystem elements. In this context, the development of marine protected areas (MPAs) in coastal waters requires careful planning around the location of desalination facilities so that connectivity between MPAs is not lost owing to the impacts of brine or thermal plumes (Heck and others, 2017); see section 3 of the present *Assessment* for additional information on MPAs. Overall, studies indicate that brine discharges have wide-ranging impacts on marine life and require continued investigations to establish specific trends, which are recognized, but findings are still incomplete.

Figure I
Desalination environmental impacts and mitigation avenues



Source: Shokri and Sanavi Fard, 2023.

Air pollution impact of desalination plants

Energy requirements for the desalination process depend upon the technology used, system details and the salinity of the water being used as source (Lienhard and others, 2016). Desalination is an energy-intensive process that still relies heavily on fossil fuels. Intensive application of energy is mainly associated with fossil fuel burning, electricity generation, plant lighting, freshwater and brine transportation (Ameen and others, 2017). Large-scale reverse osmosis plants produce water at a rate of between 2.5 kWh and 4 kWh per m^3 compared with approximately 0.3 kWh per m^3 for the treatment of conventional sources

[2] See www.sciencedirect.com/topics/engineering/intake-system.

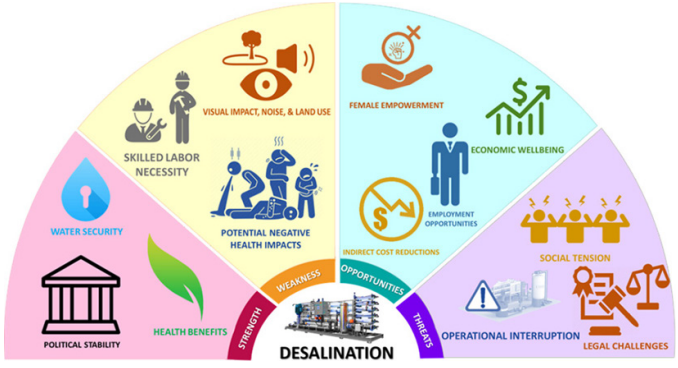
of potable water (Paraschiv and others, 2023; Zarzo and Prats, 2018). Desalination plants utilize 5% of the total energy consumed by the water sector, and that value is expected to rise to 20% by 2040 (IEA, 2016). Only 1% of total desalinated water uses renewable sources. The expected growth of desalination, if not coupled with renewable energy, will cause a projected 180% increase in carbon emissions by 2040 (Caretta and others, 2022). In addition to direct use of renewables, indirect use for desalination will also be important. When electricity production from intermittent and variable renewables exceeds demand, surplus power can be used for desalination at low cost without having to shut down generation to stabilize the grid.

The air pollution initiated by desalination plants is significant owing to greenhouse gas emissions, primarily carbon dioxide (CO_2) and acid rain gases, and other air contaminants produced during the production of electricity or steam from fossil fuels, which heavily influence the quality of air and accelerate global warming remarkably (Shokri and Sanavi Fard, 2023). While energy consumption varies according to the energy mix, the type of plant and its size, it can nevertheless be estimated that at least 120 million tons of CO_2 per year are generated by desalination sectors each year (Eyl-Mazzega and Cassignol, 2022). By 2040, installed desalination capacity worldwide is estimated to contribute 218 million tons of CO_2 annually (Shahzad and others, 2017). Lowering the carbon footprint of desalination technologies is becoming essential to reducing global warming and climate change impacts. This can be done by adopting measures towards sustainability, including improving the existing desalination systems and plants and relying on more sustainable energy sources. Mitigative strategies, such as careful selection of land and intake and outfall design, brine mining, brine treatment, the application of green desalination technologies, water and/or energy recovery, environmental impact assessment and CO_2 sequestration, can help to reduce undesirable environmental footprints (Shokri and Sanavi Fard, 2023). The use of renewable energy and mitigation strategies to minimize air pollution and climate change impacts is well established.

Socioeconomic and sociopolitical impacts

Desalination in the twenty-first century is inextricably tied to the changing paradigms of water management. Globalization of desalination is driven by techno-political factors, water management decentralization, the growing role of infrastructure as a source of revenue for financial actors entering the field of water management, and pressure to facilitate economic growth in particular economic sectors (Williams, 2022). The acceptance and proliferation of desalination systems are impacted by various environmental, economic and sociopolitical factors that are quite often intermingled and difficult to isolate (Ibrahim and others, 2021). This is especially true in regions heavily affected by climate change, where water crises and increased geopolitical risks arise. Strengthening cooperation between countries of the regions is needed to address these issues (Al-Saidi and others, 2023). Desalination is generally available to regions that can either afford the upfront costs and operational expenditure or have an attractive financial risk profile for investors. This can lead to uneven development, where profitable areas are supplied with high-quality water and unprofitable areas are left unserviced. There is a growing body of research showing that desalination, depending on how it is deployed, can exacerbate social inequalities (Fragkou 2018; O'Neill and Williams, 2024; Velásquez and Wachtendorf, 2023). The strength, weakness, opportunities and threats (SWOT) analysis of the desalination sector identifies water availability, health benefits and political stability as key strengths, with employment and female empowerment as potential opportunities (Ibrahim and others, 2021). See subsection 5B, chapter 5, for additional details on these aspects. Further studies are needed to understand the global extent of social and economic impacts of desalination systems, as current findings remain inconclusive.

Figure II
Sociopolitical factors impacting the desalination sector



Source: Ibrahim and others, 2021.

3. Sustainability pathways

Technology

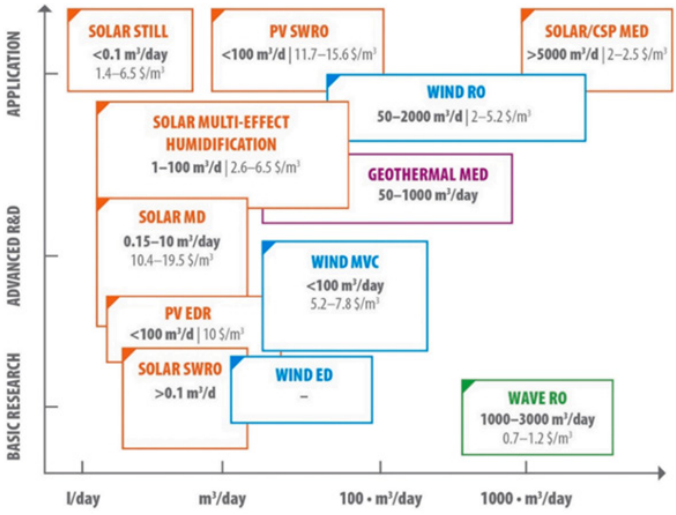
To achieve technological sustainability, efforts are focused on reducing costs and energy consumption and minimizing environmental impacts. Advances such as energy-efficient pumps, energy recovery devices and high-flux membrane materials have significantly reduced the energy consumption of reverse osmosis systems over the years (Ahmed and others, 2021). The incorporation of carbon-based, metal-oxide based and cellulose-nanocrystals based nanoparticles in desalination membranes enhances performance, positively impacting sustainability (Saleem and Zaidi, 2020). Alternative system configurations, such as closed-circuit reverse osmosis, osmotically mediated reverse osmosis and multi-pass low-rejection reverse osmosis, potentially allow reduced specific energy consumption and increased water recovery (Lin, 2019). Energy recovery devices such as pressure exchangers, Pelton wheels, Francis Turbines and hydraulic turbochargers have already been widely adopted in reverse osmosis systems to harvest hydraulic energy from brine (Das and others, 2024; Takabatake and others, 2021). Alternative technologies such as forward osmosis, capacitive deionization, membrane distillation, electrodialysis and electrodialysis reversal are aimed at cost minimization, improved plant operations, reduction in fossil fuel consumption, the use of renewable-energy sources and cutting down greenhouse gas emissions (Elsaid and others, 2020b; Mavukkandy and others, 2019).

Apart from energy and greenhouse gas-related sustainability concerns, brine disposal remains a major challenge, particularly for inland desalination plants (Mavukkandy and others, 2019). Sustainable brine management strategies are focused on reducing wastewater effluent volumes and recovering valuable materials such as water, minerals, salts and metals. To achieve this, brine discharge treatment technologies can be combined and integrated with minimal and zero liquid discharge systems. The zero liquid discharge approach is aimed at recovering 100% of freshwater while eliminating liquid waste and producing solid salt (Panagopoulos, 2022). Another potential strategy is the recovery of osmotic energy from high-salinity brine, although its cost-effectiveness has yet to be demonstrated at commercial scale (Lin, 2019; Wang and others, 2019). To mitigate the environmental impacts of high discharge temperatures on oceans, various approaches are employed, including heat recovery exchangers and low-temperature thermal desalination technologies (Curto and others, 2021; Natarajan and others, 2022). In addition, water extraction from brine supports the Sustainable Development Goal 6 targets. As desalination technologies continue to evolve, advancements in recovery and reuse of water and other key materials from brine discharges are highly likely.

Environment

Environmentally safe and sustainable management of desalination systems is essential for long-term sustainability. Key mitigation strategies include site-specific environmental impact assessments, long-term monitoring programmes tailored to desalination sites and the application of the best available technologies for managing brine effluent (Gude, 2018). The integration of renewable-energy sources – such as solar, wind and geothermal – provides viable solutions for powering desalination plants, optimizing processes and reducing both energy costs and specific energy consumption (Abdelkareem and others, 2018; Panagopoulos, 2021b; Saavedra and others, 2021). Figure III illustrates the current status of various renewable-energy technologies:

Figure III
Commercialization status of various desalination technologies

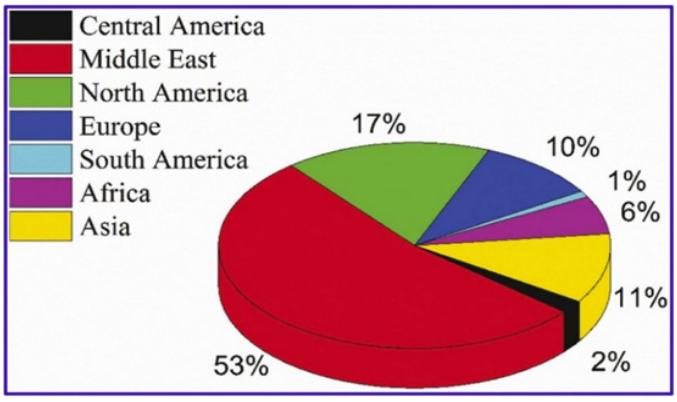


Source: Bundschuh and others, 2021.

Solar energy use with battery storage on a large scale is a promising option. Solar photovoltaic powered reverse osmosis offers an effective alternative (Bundschuh and others, 2021). With plenty of sunlight, Arab countries are the biggest users of solar-powered desalination plants,

followed by the United States, Australia, China, Central European countries, Mediterranean countries and Japan (Almasoudi and Bassam, 2024). The following schematics show solar energy usage in desalination plants.

Figure IV
Solar-powered desalination plants



Source: Almasoudi and Bassam, 2024.

Wind energy has matured into reliable technology, with many seawater reverse osmosis plants implemented in Australia (Voutchkov, 2023). After solar energy, wind power is the second most frequently used renewable-energy source for desalination plants. Constantly rising wind power production accounted for 18% (1,134 TWh) of the world's electricity production from renewable-energy sources in 2017 in onshore and offshore applications. Direct wind power use for desalination plants would partially alleviate power grid flexibility and reduce environmental impact by up to 75% as compared with fossil fuels (Greco and others, 2021). Hydraulic pressure stored in deep seawater can also output stable and successive energy flow (Cui and others, 2021). Also, countries such as India, China, the United States,[3] Pakistan and Iran account for between 56% and 62% of global desalination demand for the irrigation sector. Through irrigation efficiency growth rate improvements, global desalination demand can be reduced by as much as 30% and 60% by 2050 (Caldera and Breyer, 2020). Additional studies are needed for the desalination sector, to explore and establish the environmental benefits of replacing traditional fossil fuels with alternative renewable-energy sources.

Management

Proper management of the desalination sector is necessary to minimize maladaptation and legal issues (Campero and Harris, 2019). Key challenges include the disproportionate burden of tap water pricing on vulnerable households as compared with continental water sources (Vicuña and others, 2022) and reduced incentives for adaptation owing to the perception of seawater as an infinite resource (Fragkou and Budds, 2020), inter alia. To achieve sustainable desalination management, desalination plants are focused on optimizing resource use, ensuring operational continuity and implementing risk mitigation strategies (Al-Saidi and others, 2023). The integration of systems, such as geographic information systems (GIS) and supervisory control and data acquisition (SCADA), plays a crucial role in preventing water shortages. GIS enables visualization, analysis and asset management of desalination networks, while also assisting with data representation and spatial analysis through advanced tools (Kamal and Ali, 2024). Compliance with environmental regulations requires the continuous monitoring of operational impacts and adherence to legal thresholds (Al-Saidi and others, 2023). Desalination plants implement comprehensive systems to predict, monitor and mitigate potential ecological impacts throughout all project phases, from planning and design to construction and operation (Voutchkov and others, 2019).

Economy and market

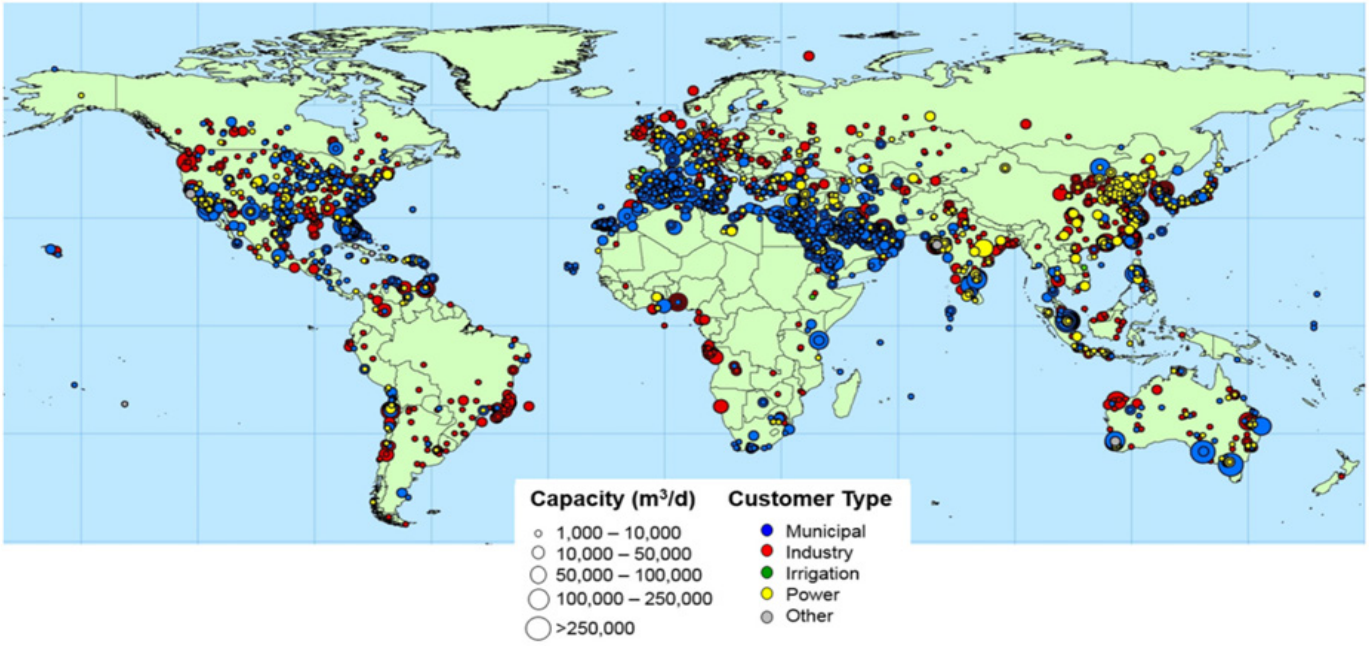
To cope with increasing water stress, the desalination industry is growing rapidly and emerging as one of the leading solutions. The majority of this growth has been in seawater rather than brackish water desalination. Desalination requires complex technology and significant capital expenditure with upfront investment. The capital expenditure for a desalination plant is estimated at between $0.65 million and $1.2 million for every 100 m^3 per day of desalinated water (Eyl-Mazzega and Cassignol, 2022). Plant operating costs are high, mainly involving energy use, labour, replacements and chemicals. Of these, expenses from thermal and electrical energy are expected to be 50% of the total cost (Nassrullah and others, 2020). Average desalinated water production cost ranges from $0.50 per m^3 for large plants to more than $1.25 per m^3 for smaller plants. For mega plants in the Persian Gulf, production cost has reached competitive pricing of below $0.50 per m^3 (Eyl-Mazzega and Cassignol, 2022). Since 2010, global installed capacity for water production from desalination plants has increased at an average rate of 7% per annum,

[3] See www.sciencedirect.com/topics/earth-and-planetary-sciences/united-states-of-america.

corresponding to approximately 4.6 million m^3 per day yearly (European Union, 2024). By 2027, the global desalination market – which was estimated to be worth $17.7 billion in 2020 – is projected to grow to $32.1 billion. From 2020 to 2027, the desalination sector is expected to expand at a robust CAGR of 9.51% worldwide (Do Thi and others, 2021). Figure V shows the size and spatial distribution of desalination facilities (>1000 m^3 per day) (Jones and others, 2019). Given past trends and current water scarcity challenges, it is highly likely that the number of desalination plants and global installed capacity will continue to increase in the future.

Figure V

Global distribution of operational desalination facilities and capacities (>1,000 m^3 per day) by sectors user of produced water



Source: Jones and others, 2019.

The power industry remains the largest owner of installed capacity for industrial purposes. The Seawater and Engineering-Procurement-Construction (EPC) model is the most frequently used feed water and plant delivery methods, accounting for 57% and 71.7% of global installed capacity, respectively. Capital cost accounts for the larger share of specific water production cost (Eke and others, 2020). The number and capacity of desalination plants by geographic region, country income level and sectoral use of desalinated water suggest that half of the global desalination capacity is located in the Middle East and North Africa region, with Saudi Arabia, the United Arab Emirates and Kuwait being both the major producers in the region and globally (Jones and others, 2019). In addition, the Middle East and North African States are committing to long-term action plans that involve the development of desalination plants. In most countries in these regions, desalination capacity is expected to double by 2030 or 2050 at the latest. Although the desalination sector is dominated by the Middle Eastern countries, there is also a trend towards geographical dispersal, with markets growing in North Africa, Asia and the Americas (Eyl-Mazzega and Cassignol, 2022). Coupled with this, the importance of desalination to a growing number of industries (e.g. mining in Chile, the manufacture of semiconductors in Taiwan Province of China), climate change and other pressures on traditional water resources, desalination is likely to continue to grow as an important frontier of the blue economy (Campero and others, 2023). Europe, Africa and many other regions are experiencing a sharp rise in desalination capacities that did not support desalination in the past (Eke and others, 2020). Overall, the global footprint of desalination plants will very likely continue to expand.

4. Social components

Benefits

Seawater desalination offers numerous environmental, socioeconomic and health benefits to humanity (Ihsanullah and others, 2021). The most obvious benefit of desalination is providing drinking and domestic water to millions of people in large cities and especially dry regions (such as the Gulf Cooperation Council region) where reliable water supply is needed to sustain regional economies (Moossa and others, 2022). Many countries, such as The Bahamas, Maldives and Malta, meet all their water needs through the desalination process (UNEP, 2021). Apart from drinking and domestic water supplies, desalinated water is used in agriculture, industries, medical facilities, aquaculture and many other sectors. Water scarcity has led to the use of desalinated water for crop irrigation, especially in arid and semi-arid agricultural countries in the Mediterranean and Middle East and North Africa regions, such as south-eastern Spain and Israel (Awaad and others, 2020; Martínez-Alvarez and others, 2016). When coupled with water reuse for irrigation, desalination can reduce groundwater extraction, enhance the water cycle and support adaptation to and mitigation of climate change impacts (Pistocchi and others, 2020). Another important benefit is salt production (liquid salt). Traditionally, evaporative ponds have been used in many countries with high evaporation rates to produce salt. With the emergence of desalination plants, use of this technology for salt production has been widely reported in the literature (Ahmed and others, 2001; Ahmed and others, 2003). Regarding employment, job trends suggest that the global transition to 100% renewable energy across the power, heat, transport and desalination sectors is a widely recognized and firmly supported approach that will create more stable, local jobs essential for economic growth while reducing unemployment. Direct energy jobs across these industries are projected to rise from approximately 57 million in 2020 to nearly 134 million by 2050 (Ram and others, 2022). With its multiple benefits, desalination is increasingly being utilized beyond drinking water, proving its reliability and effectiveness across various applications.

Disbenefits

Despite its benefits, desalination has some serious drawbacks associated from its siting, functioning to the final use of produced water. Direct seawater intake at desalination plants can absorb planktonic organisms, fish eggs and larvae, inter alia, affecting traditional small-scale fishing (Missimer and Maliva, 2018). In the same vein, brine discharge may affect local marine flora and fauna, and discharges can reduce fish populations owing to salinity and temperature increase, thus affecting activities that depend on marine resources (Kelaher and Coleman, 2022; Omerspahic and others, 2022). Other impacts of the plants siting are related to land-use conflicts as desalination may compete with recreational coastal activities. Water scarcity has also led to the use of desalinated water for crop irrigation in the Mediterranean and Middle East and North Africa regions (Awaad and others, 2020; Martínez-Alvarez and others, 2016). Although desalinated water is an abundant and climate-independent source, the use of desalinated seawater in agriculture is associated with a series of drawbacks such as high boron concentrations, a lack of plant nutrients (as compared with continental water sources), an accumulation of sodium in soil structure and the high cost. These downsides of desalination technology make it viable mostly for high-value crops (Kaner and others, 2017; Martínez-Alvarez and others, 2016). Lastly, the use of desalinated water for human consumption may not guarantee water security or eliminate scarcity on smaller scales, such as that of the household (McEvoy, 2014; Fragkou and McEvoy, 2016), while its integration into urban supply networks may increase the cost of tap water (Ricart and others, 2021), modify its organoleptic characteristics (Shomar and Hawari, 2017) and receive lower consumer approval (Hurlimann and Dolnicar, 2016). What is more, studies on the health impacts of long-term desalinated water consumption indicate a decrease in magnesium levels (Ben Zaken and others, 2020; Koren and others, 2017), a below-average iodine intake (Ovadia and others, 2016) and a wide variability in concentrations of inorganic chemicals that are below or above the World Health Organization (WHO) recommended limits for drinking water (Rizk, 2009). Owing to multiple disadvantages, extensive studies are needed to properly establish correlations between desalinated water, human health impacts and effects on agricultural practices.

Equity

Various benefits and disbenefits associated with desalination are unevenly distributed, creating winners and losers. These highly context-specific benefits or burdens of desalination reflect on and reinforce existing

socioeconomic inequalities. In a society where the water system is characterized by entrenched inequality and structural problems, the introduction of desalination is likely to exacerbate these issues, whereas in a context characterized by a greater degree of equity, the benefits and disbenefits of desalination are likely to be more evenly spread (Fragkou, 2018; McEvoy, 2014). There is a growing body of research analysing the implications of desalination for equity and environmental justice (O'Neil and Williams, 2024). The high cost of desalination facilities compared with conventional water source options almost always contributes to rising water prices for consumers, unless subsidized by States or charities, which can create a burden on poorer households. Furthermore, it has been demonstrated that, in contexts where water supply systems are fragmented, or where there is no universal networked access to water, the introduction of desalination can further drive fragmentation, often supplying more affluent areas with high-quality water and leaving less profitable areas underserviced (Fragkou, 2018; Velásquez and Wachtendorf, 2023). As desalination technologies are increasingly rolled out in the global South, there is growing concern that in certain contexts they may have the unintended consequence of increasing water inequalities (Millington and Scheba, 2021; Williams and others, 2023). Inequalities exacerbated by desalination plants are site specific, widely spread across the sector and unresolved.

Gender

A World Bank utility survey from 64 utilities in 28 economies around the world suggests that women are underrepresented in the water sector. Despite a growing understanding of the importance of incorporating women in water management and industry, women represent barely 18% of water utilities employees and occupy approximately 23% of engineering and managerial positions in the water sector. This reflects the low presence of women in science, technology, engineering and mathematics (STEM) professions, which is a global trend that is gradually changing (World Bank, 2019b). There are some specific examples of this situation being overturned in the desalination sector, such as training programmes in the field of reverse osmosis exclusively for women in Saudi Arabia (SWM, 2022). In line with this trend, women also tend to have less knowledge of coastal processes and marine ecosystems, which prevents them from taking informed decisions or participating in coastal decision-making processes related to desalination (Heck and others, 2018a). Existing data establish that the desalination workforce is disproportionately distributed among genders, with an underrepresentation of women.

Public perception and acceptance

Public awareness and acceptance is an important aspect with infrastructure projects built to serve the public good. Regarding desalination, social preference and general public perception have been greatly influenced by coastal environmental effects and high energy consumption. Despite the benefits of new desalination projects, they often face strong opposition from a significant portion of society (Ibrahim and others, 2021). Opposition to or acceptance of desalination projects also depend on biological, ecological and environmental impacts, "not-in-my-back-yard" attitudes, the influence of sociodemographic variables (such as gender, age, education and race) on public acceptance (Haddad and others, 2018), concerns about marine impacts and lack of institutional trust (Heck and others, 2018b), inter alia. As the use of seawater desalination continues to grow and large-scale desalination plants become more common, public opposition to desalination projects has also grown. While multiple surveys and studies have shown that the general public is supportive of seawater desalination, many environmental organizations and other public advocacy groups have become outspoken critics of desalination projects (Liu and others, 2022; Haddad and others, 2018; Dolnicar and others, 2011). Desalination projects have been adapting to these concerns by developing greener, more sustainable approaches and establishing public-private partnerships for project development and governance. However, public perception of and support for desalination systems remain uncertain and are not yet well established.

5. Governance

Standards and frameworks

Clear rules, standards and frameworks contribute to achieving an open and transparent decision-making process for the permission and regulation of desalination projects (UNEP, 2008). These standards typically involve guidelines for the monitoring of design, construction, water quality, water excellence parameters, pollution,

emissions, impacts on marine life and related aspects. In 1984, WHO first published the *Guidelines for Drinking-Water Quality* for safe drinking water supplies, covering a broad spectrum of contaminants and aimed at typical drinking water sources and technologies. There have been several updates and editions of the *Guidelines* (1993, 1996, 1997, 2006, 2008, 2017 and 2022) (WHO, 2008, 2009). In 2003, UNEP/MAP published "Sea water desalination in the Mediterranean assessment and guidelines" to offer a common management approach for desalination projects, and it has been widely used by the Contracting Parties for monitoring desalination projects (UNEP/MAP, 2003). The UNEP report, *Desalination Resource and Guidance Manual for Environmental Impact Assessments*, was published in 2008, in association with WHO, offering guidance to regulators, project designers and decision makers to anticipate and address all relevant concerns associated with desalination projects and achieve maximum beneficial use of water (UNEP, 2008). To cover health and environmental aspects of desalination developments and supplement the *Guidelines*, WHO also prepared the document "Safe drinking-water from desalination" in 2011 (WHO, 2011).

Legality and transboundary conflicts

Technical approval, financing and legal due diligence are essential for the successful completion of desalination projects. The formalization of projects and the relationships among the stakeholders involved are established through various contracts, including partnership agreements, framework agreements, agreements between lenders and guarantors, financing contracts, construction and operations contracts, water purchase and sale contracts, as well as lease and land-use contracts (Montano and others, 2021). Federal and state-level regulatory standards and permits are important for proper execution and handling of sensitive environmental aspects (Alonso and Melián-Martel, 2018; Younos and Lee, 2019). Regarding transboundary relations, the role of desalination is increasing in national strategies. Desalination provides countries with greater flexibility in negotiations; however, it can also reduce incentives for cooperation. These dynamics are most common in basins where at least one country is highly developed. However, desalination is also playing a role in transboundary basins such as the Nile and Mekong (Katz, 2021). Some studies suggested that desalination can lead to greater cooperation between neighbouring States, either by reducing dependence on transboundary resources, such as rivers or aquifers, or by opening up new opportunities for cooperation, such as energy-for-water agreements (Aviram and others, 2014; Bromberg and others, 2020). Others, by contrast, have suggested that these technologies may exacerbate uneven power relations and tensions between States (Katz, 2021).

Stakeholders engagement

To ensure transparency and address any community concerns, stakeholders' engagement is necessary during the planning, decision-making and implementation process (UNEP, 2008). From the 1980s, global acceptance of integrated water resource management has led to the decentralization of water management. Integrated water resource management also increased prospects for greater accountability, environmental sustainability, transparency, equity and stakeholder participation in water management processes (Patel, 2023). International and regional guidelines from organizations such as UNEP, the Organisation for Economic Co-operation and Development (OECD), the International Dispensary Association foundation, the European Union and the United States Environmental Protection Agency provide frameworks to standardize these practices and stakeholder involvement in water governance. For example, OECD requirements for stakeholder engagement in water governance are focused on recognizing different actors with a stake, their varied responsibilities, encouraging stakeholders' capacity development, assessing and evaluating engagement processes, promoting conducive institutions, paying attention to underrepresented groups and identifying appropriate stakeholder engagement initiative (Wehn and others, 2019). Among integrated water resource management principles, stakeholder participation in desalination projects is considered a democratic right in many places because it is claimed to increase accountability, legitimacy and trust in governance (Patel, 2023). Stakeholder engagement is a valuable tool for developing the common understanding of context that is needed for making sustainable water management decisions (Megdal and others, 2017).

Significant emphasis is placed on the role of the private sector in delivering desalination projects through public-private partnerships. This focus is evident both within the industry and among Governments and utilities in countries where desalination is widely deployed. One major impact of the expansion of desalination has been the acceleration of trends towards the privatization of water supply – or at least an increasing influence of

private sector actors in water resource management (Loftus and March, 2016; Williams, 2018). Economically, these financial actors provide essential capital for infrastructure projects, but may also lead to higher tariffs, disproportionately affecting low-income households. In this context, public-private partnerships have gained popularity as a means to integrate private sector actors into the provision of government services. Global trends indicate a growing reliance on public-private partnerships in the desalination industry, particularly in countries such as Australia, Israel and the United States. Research also suggests that the public sector depends on private partners for the design, construction and operation of desalination plants, regardless of the level of public financing (Greer and others, 2021). While public-private partnerships play a crucial role in fostering balanced growth within the desalination sector, their long-term effectiveness remains an area of ongoing evaluation.

Cultural considerations and Indigenous rights

An estimated 476 million Indigenous people live in more than 90 countries around the world. Globally, they represent 18.7% of the extremely poor and approximately 33% of those living in extreme poverty in rural areas (OHCHR, 2022a). Indigenous Peoples' social, cultural and economic conditions distinguish them from non-Indigenous sections of society (Cap-Net UNDP, 2018). Traditionally, water quality in Indigenous territories has been preserved owing to their sustainable practices and the inaccessibility of many of these areas. However, the growing impacts of extractivism on natural resources and climate change have increasingly threatened access to safe drinking water, posing challenges under international human rights standards. Water pollution and lack of consultation on policies and projects affecting water and sanitation rights have undermined their access to clean water (OHCHR, 2022a). Lack of access to safe drinking water also disproportionately affects Indigenous women and girls (OHCHR, 2022b). In this context, the establishment of desalination plants in regions inhabited by Indigenous Peoples can pose challenges to cultural considerations and traditional practices. This is why it is crucial to consider that water and culture are strongly interlinked when implementing a desalination project. Indigenous knowledge related to water management and governance should be understood. The inclusion of cultural context is necessary in finding sustainable solutions in water governance (Angelakis and others, 2021; Heinrichs and Rojas, 2022). The relationship between the desalination sector and its impact on global Indigenous societies is not yet properly established and hence needs to be investigated further.

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Chapter 9
Coastal development

Key points

- As a focal point of global urbanization, the coastal zone faces multiple pressures from human activities, land-sea interactions and natural disasters. Over the past five years, population, communities and infrastructure in coastal zones have consistently grown, alongside gradual economic recovery. Coastal pollution has become more complex owing to climate change and the coronavirus disease (COVID-19) pandemic, necessitating enhanced monitoring and control measures. Public participation has been diversified but still faces difficulties in awareness-raising, policy strengthening, equity and comprehensiveness.
- For the coastal zone, integrated management will continue to be needed in order to achieve a balance between economic performance and ecological environment. Climate change will be a key factor to consider in every aspect of coastal zone development. To build inclusive, safe and disaster-resilient communities while reducing negative environmental impacts and achieving a sustainable coastal economy, greater emphasis must be placed on green-grey infrastructure, ecosystem-based approaches, institutional integration and sociocultural aspects. In addition, urgent breakthroughs are needed in areas such as data collection, technology synthesis, integrated land-sea management, transboundary cooperation and policies and technical innovations related to natural and nature-based features and nature-based solutions.

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1. Introduction

The coastal zone is broadly defined as the transition region where the land meets the ocean, encompassing both the shoreline and the adjacent marine environment and the terrestrial environment influenced by the presence of the sea. More specifically, the near-coastal zone is defined as land within 100 km of the coast and at an elevation of up to 100 m (Small and Nicholls, 2003). The low-elevation coastal zone, which is often used as a proxy for land potentially at risk for future coastal hazards, refers to land with an elevation of up to 10 m (McGranahan and others, 2007).

The coastal zone supports a myriad of productive and valued ecosystems that are interdependent. These areas are essential for human settlements and cultural values, including for fisheries, tourism, recreation and trade, with associated susceptibility to pressures from various activities. Coastal zones are also susceptible to natural hazards such as tropical storms, tsunamis and sea-level rise. As climate change accelerates, the intensity of these hazards is expected to increase, making the management of these areas more critical and complex. Under multiple threats, integrated approaches must be adopted to balance ecological health, economic performance and social well-being.

In recent years, topics such as the impacts of human activities, land-sea interactions, climate change adaptation and science-management-policy translation mechanisms have been receiving increasing attention. This chapter contains an analysis of the current status of urbanization, economy and pollution of coastal zones at a global level and a summary of the development of relevant nature- and ecosystem-based solutions and approaches, as well as public participation, to provide management insights for future development.

2. Pressures and impacts

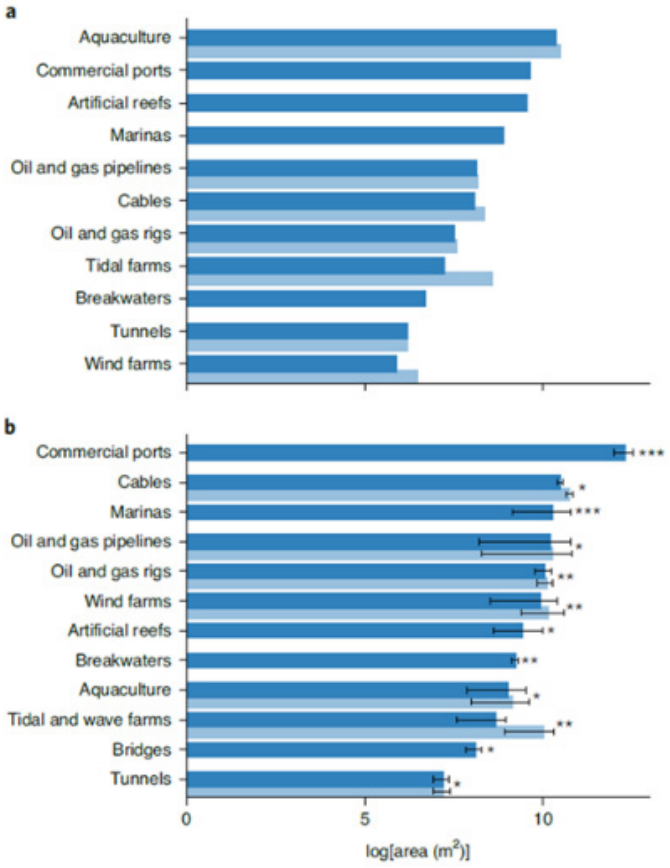
Status and trends in populations and infrastructure

The coastal zone contains some of the world's most densely populated and fastest-growing urban areas, as well as many smaller communities. Globally, approximately 2.15 billion people live in the near-coastal zone and 898 million live within the low-elevation coastal zone (Reimann and others, 2023). This represents a significant increase from 1990, when an estimated 1.2 billion people lived in the near-coastal zone (Small and Nicholls, 2023). Coastal populations are especially concentrated in East, South-East and South Asia (Center for International Earth Science Information Network, 2024). Although estimates vary, the number of people living in the near-coastal zone and low-elevation coastal zone could increase to 2.9 billion and 1.2 billion, respectively, by 2100 (Reimann and others, 2023). In some coastal areas, the population is anticipated to grow by more than 60% within the next decade (Geiß and others, 2024).

Coastal infrastructure includes coastal and foreshore defence structures, residential and commercial developments, transport and tourism/recreational facilities and energy and food production-related structures (Firth and others, 2016). A quantitative assessment of the global extent of such structures was not available at the time of publication of the second *World Ocean Assessment*. Bugnot and others (2021) estimated the combined physical footprint of marine-built structures (covered in sect. 4, chap. 6) and coastal built structures (described here) to be at least 32,000 km^2 worldwide as at 2018, expected to increase to 39,400 km^2 by 2028 (see figure). The area of seascape modified around structures was 1.0–3.4 × 10^6 km^2 in 2018. The exclusive economic zone with the greatest amount of marine-built structures was China, followed by the Republic of Korea and the Philippines. Most of the physical footprint of wind and tidal farms was located on the coast of the United Kingdom of Great Britain and Northern Ireland, with the rest spread along the coasts of North America, India, Germany and in the Asian North Pacific. Tunnels and bridges were mainly located in the northern hemisphere; breakwaters for coastal defence occupied the greatest amount of area in Italy; and 34% of marinas were in the United States and Canada. However, the physical footprint of breakwaters for regions with substantial coastal modification (for example, China) was not available (Bugnot and others, 2021). The availability and quality of data on the extent of infrastructure vary depending on structure type and geographic location. Data for regional industries such as recreational marinas and aquaculture are particularly incomplete (Bugnot and others, 2021). It is especially challenging to quantify structures that are static throughout much of their lifespan but are occasionally moved to other locations, such as floating docks, homes, lodges and aquaculture facilities (Iacarella and others, 2019).

Figure

Global extent of marine and coastal construction: area of physical footprint in 2018 (dark blue bars) and predicted for 2028 (light blue bars) (a); and modification of surrounding seascapes, by type of built structures (b)



Source: Reproduced from Bugnot and others, 2021, with permission.

Note: Marine structures (oil and gas pipelines and rigs and cables) are covered in sect. 4, chap. 6. Future projections were available only for aquaculture, submarine cables, wave, tidal and wind farms, and oil and gas pipelines and rigs; no wave farms were operational up to 2018, hence only future projections are presented.

* Scale of seascape modifications: adjacent (<100 m); ** scale of seascape modifications: local (>100 m to <10 km); *** scale of seascape modifications: regional (>10 to hundreds of kilometres).

The projected increase of human population living in the low-elevation coastal zone (Kulp and Strauss, 2019) will continue to prompt many of the world's coastal cities to extend their boundaries seaward by filling in coastal wetlands and shallow seas. Sengupta and others (2023) quantified coastal reclamation by 135 major coastal cities around the world, finding that 78% (106 out of 135) of these cities had reclaimed a total of 253,000 ha of additional land from 2000 to 2020. Reclamation is a global-scale phenomenon in the twenty-first century, especially prominent in East Asia, the Middle East and South-East Asia, followed by western Europe and West Africa. The most common (>70 cities) land uses on reclaimed spaces are port extensions (Sengupta and others, 2023), a trend that may continue owing to sustained increases in container shipping volume around the world (World Shipping Council, 2024). Of the top 50 countries expected to experience the fastest population growth from 2020 to 2100, 86% are African, of which 72% are coastal (United Nations, 2017). Many of these countries are characterized by some of the largest remaining stretches of "unaltered" coastlines (Firth and others, 2016), by contrast with, for example, the United States, where more than 50% of natural shorelines have been replaced by seawalls, breakwaters and other hard structures (Gittman and others, 2016).

Increasing climate risks for urbanization

Growth in coastal urban areas and communities increases the coastal hazard exposure for populations (Magnan and others, 2016), infrastructure such as ports (Izaguirre and others, 2021) and roadways (Koks and others, 2019), economic assets (Kummu and others, 2016) and cultural heritage (Reimann and others, 2018). As noted in chapter 8 of the second *World Ocean Assessment*, the vulnerability of coastal communities to the impacts of climate change is also increasingly concerning (United Nations, 2021). However, the quantification of climate risks is difficult owing to a variety of uncertainties, including future socioeconomic policy scenarios, anticipated physical processes and model limitations (Rising and others, 2022). Risk is therefore often reported in terms of expected levels of impact and central confidence bounds, as opposed to probabilities.

According to the Intergovernmental Panel on Climate Change (IPCC), there is high confidence that projected climate risks will increase with greater exposure to ocean-driven hazards (Glavovic and others, 2022). IPCC (2022) reports with medium confidence that, if global mean sea-level rises by 0.15 m relative to 2020 levels, the population exposed to a 100-year coastal flood is projected to increase by 20%. There is high confidence that coastal flood risk will rapidly increase by 2–3 orders of magnitude by 2100 and medium confidence that this will result in the exposure of $7 trillion to 14 trillion of coastal infrastructure assets (Glavovic and others, 2022). While there is significant regional variation, risks are especially acute for urban areas and communities located in the Arctic (Tanguy and others, 2024), on low-lying or

subsiding small islands (Storlazzi and others, 2018) and along estuarine and deltaic coasts (Nienhaus and others, 2023). Under all climate and socioeconomic scenarios, IPCC (2022) reports with very high confidence that such high-risk areas and communities will experience severe disruption by 2100, with some experiencing such disruption as early as 2050.

Risks to coastal urban areas and communities depend on not only hazard exposure but also vulnerability, in terms both of social conditions (i.e. susceptibility) and capacity to respond (i.e. resilience) (Steven and others, 2020). While vulnerability varies by country, in a recent cross-country comparison, developed countries were found to be significantly less susceptible and better equipped to deal with climate risks than developing countries (Saeed and others, 2023). Developing countries are often more susceptible owing to poor natural and built environments, poverty and weak socioeconomic status (Hamidi and others, 2020). Developing countries also tend to have less capacity to combat climatic events, as compared with developed countries that have greater stocks of capital that can be mobilized to combat climate risks (Millner and Dietz, 2015). While no country can escape climate risk, exposure, susceptibility and resilience interact in a dynamic process that results in an uneven distribution of vulnerability that is not strictly environmental but also social and economic (Thomas and others, 2019).

Economic performance

The coastal economy refers to all economic and industrial activities that take place in or around coastal areas. The activities represent a significant proportion of global gross domestic product (GDP) owing to their economic diversity. The coastal economy is also a major driver of employment in many coastal regions, especially in developing countries, where it provides crucial opportunities for local communities. The COVID-19 pandemic had a significant impact on the global coastal economy, with disruptions to trade, tourism and supply chains. Coastal areas experienced economic contraction at the start of the pandemic, but recovery has varied by region and sector. Coastal tourism saw a dramatic decline in 2020, with a decrease in international arrivals of more than 70% as compared with 2019, according to the World Tourism Organization.

In 2021, economic recovery was uneven. Coastal areas in developed countries, such as the United States, and in Europe, generally experienced a faster recovery thanks to economic stimulus plans and effective vaccination campaigns. Conversely, coastal areas in developing countries had slower recoveries owing to structural challenges and a heavier reliance on tourism. According to data from the World Bank and the International Monetary Fund (IMF), the global coastal economy has shown an average growth of 3% to 4% per year since 2022, with significant variations depending on the region and sector. Since 2021, trade volumes have rebounded, with robust growth in imports and exports. Data from the World Trade Organization (WTO) show an average growth in global trade volumes of 5% to 6% per year since 2022.

Coastal pollution

Coastal pollution is a pervasive and growing problem worldwide, threatening the health of marine ecosystems, human well-being and the economy. The coastal zone is vulnerable to pollution owing to its proximity to human activities such as industrialization, agriculture and urbanization. Pollution in coastal areas includes plastic debris (Bessa and others, 2018; de Deus and others, 2024), nutrients (Grizzetti and others, 2021; Islam and Tanaka, 2004), metals (Qian and others, 2015; Li and others, 2022) and persistent organic compounds (Nunes and others, 2011), inter alia. Different geographical regions have faced different challenges over the past few years, such as the rapid industrialization and inadequate waste management in Asia-Pacific, the dense shipping lanes, oil rigs and agricultural run-off in the Mediterranean and the limited waste management infrastructure in Africa (UNEP, 2019; European Union, 2020).

There are also many new perspectives that deserve attention. Global issues of marine pollution are interlinked with climate change, and understanding these connections is key to managing these combined risks (Lincoln and others, 2022; Ford and others, 2022). For instance, extreme weather events contribute to debris of various shapes and weights known to exacerbate the overall damage to the coastal environment through collision and damming loads (Park and others, 2021; Chowdhury and others, 2024). Haarr and others (2022) argue that the geographical distribution of empirical data on marine litter stranded on coastal zones corresponds relatively poorly to the estimated geographical differences in annual mismanaged plastic waste (Lebreton and Andrady, 2019). Western Asia, Europe (excluding eastern Europe), the Caribbean, North America and Oceanic countries contribute relatively little mismanaged plastic waste but have been comparatively well studied. Conversely, Africa, Asia (excluding western Asia) and central America have

been poorly studied, although they have high rates of mismanaged plastic waste. This suggests a mismatch between poorly managed plastic waste and research initiatives documenting the problem. Plastics are the most abundant waste category in coastal environments (Iñiguez and others, 2016), and it should be noted that the global COVID-19 outbreak is estimated to have contributed an extra 3.4 billion single-use facemasks/face shields daily (Benson and others, 2021). An assessment of the direct economic costs of marine litter for a coastal region demonstrated that marine litter created costs and inconvenience for stakeholders engaged in marine activities, leading to significant financial burdens for small communities (Rodríguez and others, 2020).

3. Sustainability pathways

Climate change adaptation

Natural coastal habitats can provide an effective first line of defence against climate change-related issues (Reguero and others, 2018; Sun and Carson, 2020). However, these natural protection services may be compromised as coastal habitats are degraded or lost owing to sea-level rise, water level fluctuations and encroaching coastal development (Arkema and others, 2013; Quataert and others, 2015; Crosby and others, 2016; Narayan and others, 2017). The proliferation of marine-built structures provides a suite of benefits but can also have unintended and sometimes hidden costs. The artificialization of the global coastline and the threats posed by the warming climate are driving humanity to develop novel solutions that halt biodiversity and habitat loss and enhance the marine-built environment. Under these circumstances, enhancing environmental quality in heavily urbanized areas, adapting urban areas and the conservation, restoration or construction of coastal natural and nature-based features can provide a potential pathway to accomplish the multiple goals of managing coastal hazards, restoring native biodiversity and sustaining ecosystem functions and services (Mayer-Pinto and others, 2017; Morris and others, 2018, 2019; Airoldi and others, 2021; Bridges and others, 2021; Firth and others, 2024). Hence, integrating natural and nature-based features and eco-engineering into nature-based solutions is beneficial for addressing challenges posed by climate change, benefiting both people and nature.

Natural ecosystems in urban areas, such as estuarine margins and coastal beachfronts, can be restored to enhance ecological health and resilience. Such actions can be achieved through soft or hybrid eco-engineering approaches (Dafforn and others, 2015a; Morris and others, 2018, 2019; Firth and others, 2024). Ecological or green coastal and marine eco-engineering involves the use of natural materials and processes to enhance coastal resilience and restore ecosystems, such as planting mangroves or marsh grasses. Hybrid green-grey eco-engineering combines ecological approaches with traditional grey engineering techniques, such as integrating oyster reefs with seawalls or building concrete base structures and outplanting corals on top of them to provide both ecological and structural benefits. Currently, these initiatives are mostly concentrated along coastlines in temperate regions (Bridges and others, 2021). While integrated green-grey infrastructure is gaining significant attention from a policy standpoint, there is still limited research from engineering, scientific or economic perspectives regarding its integration and implementation (Kuwae and Crooks, 2021; O'Shaughnessy and others, 2020; Chavez and others, 2021; Viehman and others, 2023).

This underscores the urgent need to expand and accelerate such practices in other regions of the world, particularly in developing nations, which often have more people living in vulnerable areas and where coastal urbanization is occurring more rapidly (Firth and others, 2016; Merkens and others, 2016; Reimann and others, 2023). Hard, grey coastal and marine eco-engineering offers a viable solution in urbanized areas modified by artificial structures, relying on local knowledge to achieve these goals (Strain and others, 2018). It can adapt traditional engineered structures such as seawalls and breakwaters with more complex designs to enhance local biodiversity and ecosystem services (e.g. Adams and others, 2021; Morris and others, 2018; Vozzo and others, 2021). This method could also be applicable to future interventions where green approaches are not feasible (Morris and others, 2018, 2019), distinguishing itself from traditional engineering by prioritizing environmental sustainability. It is important to recognize that the above methods may not be universally applicable or inherently sustainable (Parkinson and Ogurcak, 2018). Implementing grey, green or hybrid eco-engineering requires careful planning and further research, with caution to prevent "greenwashing" or "blue-washing" (Dafforn and others, 2015a, 2015b; Firth and others, 2020, 2024). Adaptive monitoring programmes

with appropriate quantitative measures are also needed to evaluate and enhance the efficiency of interventions to protect coastal cities (Bredes and others, 2024).

Despite the growing body of knowledge on nature-based solutions, gaps remain (Lacambra and others, 2024; Seddon and others, 2020). For instance, measures to quantify the effectiveness of natural and nature-based features at mitigating coastal hazards and adapting to climate impacts are still lacking (Viehman and others, 2023). Owing to the site-specific nature, decision makers often lack information on assessing their suitability in different environments. Research on natural and nature-based features suitability and monitoring is yet to be institutionalized into policy, regulations and decision-making. The development of risk-based valuations of the ecosystem services attributed to natural and nature-based features has been limited by the lack of high-resolution data on bathymetry, topography, ecosystems and economic assets and the difficulty in modelling complex hydrodynamic and ecological processes (Reguero and others, 2021). A better understanding of the hydrodynamics, morphodynamics and ecology across a variety of spatial and temporal scales, as well as across a range of types of natural and nature-based features, is critical for clearly defining the benefits of natural and nature-based features and advancing nature-based solutions.

The gaps in understanding also proliferate owing to a lack of studies on the broader effectiveness and the context-dependence of coastal nature-based solutions, including the scale of implementation, ecological characteristics and socioeconomic conditions. Specifically, there is a need for more empirical evidence on the long-term effectiveness and cost-benefit analysis of nature-based solutions as compared with traditional grey infrastructure. Chausson and others (2020) found that performance indicators, including cost, were broadly assessed for approximately 10% of coastal nature-based solution projects, including coral reef, mangrove, seagrass and saltmarsh restoration. This uncertainty also extends to grey infrastructure; however, a key difference between nature-based solutions and grey infrastructure is that nature-based solution adaptation services are hypothesized to increase over time, while grey infrastructure adaptation services may decline (Avery and others, 2023; Feagin and others, 2021).

Monitoring and control network

Coastal areas face ongoing threats from various pollutants and challenges from natural processes, such as coastal erosion, sea-level rise and the degradation of cliffs and beaches. Effective monitoring and control networks are crucial to mitigate these impacts and preserve coastal environments.

An example is presented for harmful algal blooms (red tides) and hypoxia (also known as “dead zones”), which can usually be monitored using in situ measurement, remote-sensing and numerical modelling methods (e.g. Liu and others, 2022; Ou and Xue, 2024). Detecting and forecasting their movement using available remote-sensing and high-fidelity modelling technology are essential, since traditional ship-based field sampling and analysis are very limited in both space and temporal frequency. Many countries have established red tide or algal bloom monitoring systems relying on satellite imagery, on-site observations, models and buoy data (Lee and others, 2013; Guan and others, 2022). For example, the National Centers for Coastal Ocean Science (NCCOS) of the National Oceanic and Atmospheric Administration (NOAA) of the United States developed the Algal Bloom Monitoring System to routinely deliver near real-time products for use in locating, monitoring and quantifying algal blooms in coastal and lake regions of the United States (NOAA, n.d.). The monitoring of pollutants, such as sewage discharge, marine debris and microplastics in the ocean through remote sensing, can be effectively accomplished by using sensitivity analysis, optical simulation and satellite image spectral analysis. To improve the accuracy and reliability of marine pollutant monitoring and forecasting, it is important to integrate remote-sensing, numerical and artificial intelligence and machine learning modelling (e.g. Ou and others, 2022) with other monitoring tools such as ship sensors, buoy sensors, aircraft sensors and biosensor networks.

In terms of coastal erosion, technologies such as satellite imagery, drones and geographic information systems (GIS) are essential for tracking changes in the coastline. Near real-time data collection allows for the early identification of erosion hotspots and timely intervention. Effective mitigation strategies can be designed based on the comprehensive understanding of erosion patterns and their causes. For sea-level rise, tide gauges, satellite altimetry and climate models are critical tools for measuring and projecting changes. These provide accurate data, enabling managers to assess risks and plan adaptive measures. Early warning systems and predictive models can help prepare communities and infrastructure for future sea-level scenarios. Restoration of cliffs and beaches is essential for maintaining natural

coastal defences against erosion and flooding, which often includes beach nourishment, revetments and sea walls. It is worth mentioning that all shoreline monitoring and management require a comprehensive coastal erosion modelling study in order to assess potential impacts and design appropriate mitigation measures.

The forecast modelling process typically includes the following steps. First is gathering historical and current data on waves, tides, sediment transport and shoreline changes with technologies such as instrument moorings, satellite imagery, aerial photography and field surveys. Second is utilizing computational models such as Delft3D, MIKE 21, the Regional Ocean Modeling System (ROMS) and SWAN (and the coupling of these models, e.g. COAWST (Warner and others, 2010)) to simulate coastal processes and predict future changes under various scenarios. These models can assess the impact of new infrastructure on flooding and/or erosion patterns and identify vulnerable areas. Third is evaluating different development and mitigation scenarios to understand their potential impacts on coastal flooding and/or erosion. This includes the construction of breakwaters, jetties and other structures, as well as natural solutions such as beach nourishment and vegetation planting (it should be noted that, for eroded shores, vegetation planting requires structures that protect the planted trees from wave action to be effective). Then follows risk assessment, which identifies areas at high risk of erosion and recommended mitigation strategies. This involves a combination of engineering solutions and ecosystem-based approaches. The final step is implementing continuous monitoring programmes to track the effectiveness of mitigation measures and adapt them as necessary on the basis of observed changes and new data.

Integrated land and sea management

The ecosystem approach – a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way (CBD, 2000) – and similar concepts such as ecosystem-based management and ecosystem-based approach (Kirkfeldt, 2019) require integrated land and sea management, owing to the connectivity of terrestrial ecosystems, including watersheds and estuaries, with nearshore marine ecosystems. The concept is reflected in the classic pathway of integrated coastal zone management, which has been a policy option for more than 50 years and has been implemented in more than 100 States and regions, to promote integrated environmental protection and economic growth in the coastal zone (Ye and others, 2015; Singh and others, 2021). At present, it is also increasingly emphasized in both land planning and marine spatial planning (also referred to as maritime spatial planning) to focus on the interaction of various elements at the land-sea interface, such as sociocultural, coastal erosion and climate change factors (Maragno and others, 2020; Stancheva and others, 2021; Pikner and others, 2022).

From the perspective of planning practices, land and sea used to be studied and planned separately as two relatively independent parts, regardless of their synergistic effects. Currently, coordinated planning has become a direct means of resolving use conflicts and realizing synergistic development in many States and regions. For example, over the past five years, China has carried out reforms in spatial planning with the concept of land-sea coordination, which emphasizes seamless land and marine planning, paying attention to the coherence of different ecosystems, promoting the marine, coastal and land industry as a system and driving inland development through the marine economy. In the current Coastal Zone Plan, which is an important component of territorial spatial planning, the idea of land-sea coordination is fully emphasized through the integration of sectoral responsibilities, departmental cooperation, shoreline categorization and control and the idea of multiple plans in one (Liu and Xing, 2019; Wang and others, 2024). Another example is the United Kingdom Marine Policy Statement (2011), which makes it clear that marine planning must interact with existing terrestrial planning, especially in physically overlapping areas. Land-use plans and marine plans share many common goals. Relevant policies suggest that the coordination of marine and terrestrial planning could be achieved through maintaining the coherence of different documents, enhancing the cooperation and communication between land and sea planning authorities, sharing data in the decision-making process and following the methods and principles of integrated coastal zone management. The consideration of land-sea interactions has also been clearly stated in various documents related to European Union maritime spatial planning, but specific pathways still need to be explored with more research and practices. These initiatives could support global efforts for sustainability, as the United Nations Environment Programme (2023) highlights the need to connect land and sea planning to better manage coastal and marine resources.

Transboundary management practices

Transboundary management requires coordinated and cooperative governance of marine resources and ecosystems that span the borders of multiple States or regions, which also often involves coastal zone areas. Marine spatial planning is the most prominent governance process that implements national regulations of human activities (Stelzenmüller and others, 2018). In transboundary settings such as in Europe (Mackelworth and others, 2024) or in the Yellow Sea (Ma and others, 2023), where socioeconomic interests are confined to national management boundaries, but ecosystem health and resilience depend on ecosystem processes and exposure to human pressures at different scales, national marine spatial planning processes also face the challenge of international consultations (Elliott and others, 2023). Thus, transboundary management is confronted with a high level of complexity regarding the coordination of actions but also the enforcement and the monitoring of compliance, a lack of which can undermine the effectiveness of management regulations (Cormier and others, 2018). Next to the regulation of human activities, the implementation of marine conservation areas or marine protected areas (MPAs) may require transboundary coordination for enforcement and management efforts to ensure the protection of those areas of high conservation value and their respective assets. Examples of such transboundary management efforts can be found in the Mediterranean Sea area (the Network of Marine Protected Areas in the Mediterranean (MedPAN) or the Pelagos Sanctuary for Mediterranean marine mammals); South-East Asia and the Pacific (Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI-CFF)), the Wadden Sea (Trilateral Wadden Sea Cooperation) or the Caribbean Sea (Punta de Manabique Wildlife Refuge and Sarstoon-Temash National Park).

To bridge the gap between European maritime spatial planning frameworks and the unique challenges of the Yellow Sea, it is imperative to foster enhanced collaboration between European nations and the States bordering the Yellow Sea. The Yellow Sea Large Marine Ecosystem has a history of regional cooperation, providing a foundation for further collaboration on transboundary management (UNDP, 2021). This collaboration should be focused on the sustainable management of shared maritime resources, robust environmental protection measures and the achievement of Sustainable Development Goals. The European Union's International Ocean Governance agenda emphasizes the importance of multilateral cooperation to address global ocean challenges, which can serve as a model for the Yellow Sea region. By engaging in joint initiatives, sharing best practices (Douvere, 2008) and knowledge on enabling conditions (Zuercher and others, 2022) and aligning policies, these regions can develop harmonized maritime spatial planning approaches that effectively manage transboundary marine ecosystems and address common environmental concerns. The importance of marine spatial planning in advancing ecosystem-based sea use management is crucial for addressing the complex interactions between human activities and the marine environment (Yatim and others, 2016). Such efforts would not only enhance the ecological health of the Yellow Sea (Ma and others, 2023), but also promote socioeconomic benefits for the coastal communities dependent on these vital marine resources. Regional environmental governance initiatives, such as those focused on the Yellow Sea and Bohai Sea, offer valuable insights into the complexities of land-sea coordination in addressing pollution and promoting sustainable development (Liu and others, 2021).

The European Union underscores the paramount importance of multilateral cooperation in addressing global ocean challenges through its International Ocean Governance agenda. As a proponent of multilateral responses to global issues, the European Union endeavours to fortify the international rules-based framework. The European Union collaborates on ocean governance with bilateral, regional and multilateral partners globally, with its primary legal instrument being the United Nations Convention on the Law of the Sea. Through the European Union Maritime Security Strategy, the European Union addresses challenges impacting the security of the ocean, such as cross-border and organized crime, threats to freedom of navigation, threats to biodiversity, climate-related challenges and environmental degradation. The European Union's approach to ocean governance aligns with its broader foreign policy goals, promoting sustainable development, security and stability beyond its borders (Delmartino, 2009).

Based on past cases of transboundary marine spatial planning, experiences of transboundary management can be summarized as follows. First is the very considerable role of transboundary and regional organizations, which can coordinate different administrative bodies, facilitate cooperation and promote research and implementation in the form of various funds. The second is the need to actively play an expert consultation role, which could bring together universities and research institutes

from different regions to promote exchange and implementation. Third, the analysis and integration of different management systems and institutions, the interoperability, unification and disclosure of data and information from various sources and including various users and departments in the decision-making system are the key factors for ensuring the success of transboundary management. Fourth, communication, exchange, the identification of similarities and differences and negotiation and coordination among different management bodies are necessary throughout the process of all types of transboundary management practices.

4. Social components

Enhancing public participation

Coastal zone management is a public policy process for which community and public involvement in environmental decision-making is a critical element of governance (Edwards and others, 1997). Workshops, meetings, interviews, surveys, participatory mapping, social network analysis and virtual space are all methods to engage stakeholders and practise public participation (Ison and others, 2024; Sartorius and others, 2024). Each of these methods uniquely engages the public and gathers input; for example, workshops and meetings enable direct interaction, whereas interviews and surveys offer more in-depth responses. Participatory mapping empowers communities to visualize their environment, while social media and virtual spaces provide platforms for broader, more dynamic engagement.

While the concept is simple, the reality of encouraging participation is not. The decision on whom to include is itself challenging and fundamental to the success of the process to broaden engagement in the governance of the coast (Reed and others, 2018; Celliers and others, 2023). The importance of public participation, social equity and agency is a growing topic in both the research into and the implementation of coastal policies (Norström and others, 2020; Muhl and others, 2023; Morris and others, 2024). The practice of public participation is thus an issue strongly related to the transformation of society to sustainability, increasing social equity and enabling the inclusion of human-nature connectedness, agency and leadership in the participation processes relating to coastal management (Tallent and Zabala, 2024; West and others, 2024; Engen and others, 2024).

Public participation has long been legally embedded in the formal planning process for major developments through the process of environmental impact assessment (Johnson and Dagg, 2003). It is also already part of most coastal management frameworks (Sowman and Malan, 2018; Harvey and Clarke, 2019). Participatory GIS mapping is used as a direct means of co-producing knowledge with stakeholder and community interests (Burdon and others, 2019). Public participatory GIS (PPGIS) has been demonstrated to be a valuable tool for policy advice and promoting the inclusion and empowerment of underrepresented populations in the decision-making process. Moreover, PPGIS allows for assessing the perception and acceptability of land and marine use planning from a social perspective (Vieira da Silva and others, 2021). For instance, the New Hampshire Living Shoreline Site Suitability Assessment applied GIS-based methods to identify appropriate sites for nature-based shoreline stabilization, integrating ecological, physical and social criteria into coastal planning (Balasubramanyam and Howard, 2019). There are also several emerging approaches. Citizen science is an integral part of a burgeoning global initiative aimed at involving the community in scientific research (Elrick-Barr and others, 2023). This approach fosters collaboration between non-professionals and scientists in a reciprocal process (Garcia-Soto and others, 2021). For instance, CoastSnap is a community beach monitoring programme that transforms everyday smartphones into tools for measuring coastal responses to cyclones, sea-level rise, human modifications and other factors (Harley and Kinsela, 2022). It is expected to significantly enhance understanding of changing coastlines and provide the scientific community with robust quantitative data. Co-production of knowledge is intended to improve decision quality through deliberation and collaborative management by fostering viable, fair and inclusive decision options and solutions (Turnhout and others, 2020). For example, co-production of climate services for coastal flooding and the use of story maps offer the possibility to visualize scientific information and climate data in an accessible format and, as web-based tools, reach a large audience (Vollstedt and others, 2021). Another example is the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO-IOC) Tsunami Ready Recognition Programme, a voluntary, performance-based community

recognition programme that promotes an understanding of the concept of readiness as an active collaboration among national and local warning and emergency management agencies and government authorities, scientists, community leaders and the public to build resilient communities through the fulfilment of a set of established indicators (UNESCO, 2025).

COVID-19 posed a significant challenge for many coastal management processes. It also demonstrated that it is possible to work online with minimal impact on collaboration and engagement. While there are clear environmental benefits to public participation "going digital", it is crucial to recognize potential drawbacks. Public participation may become disengaged from coastal zone issues and management owing to a lack of digital literacy, the high costs of emerging technologies (such as virtual reality platform development) and the limited capacity to create and implement digital solutions (McKinley and others, 2021).

Enhancing participation through arts-based methods significantly contributes to coastal sustainability by raising awareness, fostering learning and promoting engagement and enjoyment among project participants (Matias and others, 2023). Greater focus is required in urban policy and academic research on the implications of creating temporary urban art spaces for immediate inclusive engagement with end users and for sustained community development (e.g. the British coast; see Zebracki, 2018). Art-science approaches could also offer valuable avenues for communication and enquiry (Paterson and others, 2020). Developing socioecological scenarios also involves a participatory process that engages stakeholders (Allan and others, 2022). Scenario development as a tool describes various potential future states and has been utilized, for example, to aid coastal adaptation planning (Gray and others, 2020). The robust and structured stakeholder engagement process fostered strong local ownership of both the scenarios and the overall process (Allan and others, 2022). Social media has emerged as a powerful tool for driving change by influencing conversations and boosting interest and participation (Vince and Hardesty, 2018). These platforms are now well established as quick and effective means of disseminating information (da Costa and others, 2020). Social media can play a crucial role in engaging society with reliable information, altering habits and promoting sustainable behaviour (Otero and others, 2021).

Human rights, equity, gender, and Indigenous, traditional owner and local community knowledge-related issues

Social equity in coastal zone management is increasingly recognized as crucial for effective and just conservation practices. It involves considering the distribution of benefits and burdens among different stakeholders, ensuring fair access to resources and promoting inclusive decision-making processes (Bennett and others, 2021). The call for equity in coastal zone management stems from the exclusion of persons in marginalized situations, including Indigenous Peoples and small-scale fishers, who rely on marine ecosystems for their livelihoods and cultural identity, from the decision-making process and benefits derived from exploitation of marine resources (Cisneros-Montemayor and others, 2019; Bennett, 2022). Despite the growing recognition, social equity is often overlooked in national-level blue economy initiatives that prioritize large, influential stakeholders (Bennett and others, 2021; Das, 2023; Thoya and others, 2022).

Take small-scale fishers as an example, who are traditional owners of fishing grounds, mostly inherited from their ancestors. Recent blue economy initiatives have encroached upon their traditional spaces, resulting in land-grabbing, displacement and environmental degradation (Bennett and others, 2021; Das, 2023; Barbesgaard, 2018). As a result, these fishers face diminished access to vital marine resources, threatening both their livelihoods and adversely impacting their human rights and well-being. The reduction in ecosystem services, such as fish stocks and clean waters, further exacerbates their challenges, leaving them vulnerable to poverty and food insecurity (Bennett and others, 2021). Similarly, women, who carry a significant role in small-scale fisheries, mariculture and post-harvest processing, contributing to both household income and food security, are often undervalued and overlooked in decision-making processes (Lentisco and Lee, 2015; de Mattos and others, 2022; Preez, 2018). They face numerous barriers in coastal zone development, including limited access to resources such as land, credit and technology. Cultural norms and gender-based discrimination further restrict their participation in governance and policymaking (Frangoudes and others, 2019; Preez, 2018).

The inclusion of Indigenous Peoples, local communities, women and girls, children and youth, and persons with disabilities in decision-making, particularly by using

traditional knowledge, is essential but often overlooked in favour of top-down approaches (Mauro and Hardison, 2000; Peci Lyons and others, 2023). To address these inequalities, a paradigm shift in policies is needed: one that integrates diverse perspectives, traditional knowledge and participatory approaches into marine policy and management (Bennett and others, 2021; Das, 2023). Ensuring the participation of local communities not only promotes fair distribution of benefits but also enhances the sustainable use of natural resources and biodiversity conservation, which are closely linked to climate change adaptation efforts (Cisneros-Montemayor and others, 2019). These rights have been recognized in legal frameworks such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), the Indigenous and Tribal Peoples Convention (ILO 169) and the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries, which have provided guidance for the inclusion of Indigenous Peoples and local communities in ocean governance at the national and local levels (Mauro and Hardison, 2000; Jentoft and others, 2017); this should be further emphasized in the future.

5. Governance

Coastal zone development faces multiple social, economic and environmental pressures from the continuing growth of populations, communities and infrastructures, especially impacts related to climate change. In the face of these circumstances, the approach to coastal zone governance must be integrated and adaptive, whether it is for economic growth, relieving various pressures or nearshore pollution management or for responding to climate change, land-sea integration and transboundary management issues. For example, the goals of coastal economic growth are multiple and aimed at maximizing economic benefits while ensuring environmental sustainability and the resilience of coastal communities. An integrated approach will help to overcome challenges and maximize benefits for all stakeholders to ensure sustainable management of the coastal zone. When looking at marine pollution from a complex systems perspective, it is not possible to separately consider land-based impacts and coastal governance. The coastal zone is the sink for many of the products and wastes of human activities, and it requires management in a much larger context (Lu and others, 2018).

Currently, coastal governance structures vary widely among States around the globe. In nations such as the United States, Brazil, India and Japan, responsibility for coastal management is often decentralized to regional or local governments within a framework established at the national level. In States such as Australia and Germany, where the coastal zone is not controlled with significant central government involvement, more streamlined and coherent policies may be implemented over a larger geographical area. The Council of Europe promotes local governance in coastal management, emphasizing that local authorities can best understand and address the specific challenges in cooperation with local stakeholders (Toledo and others, 2024). Many States have established relevant legislative frameworks for coastal governance, but implementation enforcement varies significantly (Kay and Alder, 2017). At the global level, recommendations for coastal zone governance tend to be biased towards a characteristic goal, although integrated pathways are constantly emphasized. For example, IPCC suggests that a mix of infrastructural, nature-based, institutional and sociocultural innovations is needed to reduce the climate change-compounded risks to coastal urban areas and communities. Overall, despite the consensus on an integrated management pathway for coastal zone development, current research and regional management structures still tend to be fragmented or single-targeted. There is an urgent need for targeted guidelines or initiatives for coastal zone governance at the global level that encompass legislation, institutionalization, hierarchical relationships, the balancing of socioeconomic-environmental elements and adaptation to climate change.

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Chapter 10
Geoengineering

Key points

- The scientific consensus remains that proposed novel geoengineering approaches are unproven in practice, and there is significant uncertainty about the impacts of pilot studies and upscaled experiments, especially where these experiments are planned over large ocean areas.
- Paris Agreement-compliant Intergovernmental Panel on Climate Change (IPCC) scenarios indicate that 7–9 gigatons of carbon dioxide ($GtCO_2$) removal (CDR) would be needed per year by 2050, in addition to reductions in greenhouse gas emissions. Currently only 2 $GtCO_2$ p.a. of conventional, low-durability terrestrial CDR has materialized.
- Monitoring, reporting and verification (MRV) protocols will be key to determining whether marine CO_2 removal (mCDR) approaches are effective.
- mCDR research studies may advance the state of key knowledge in the coming decade.
- Governance frameworks are limited and fragmented. Efforts to develop an international legally binding governance framework under the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and its 1996 Protocol (London Protocol) are progressing.

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1. Introduction

This new chapter in the *World Ocean Assessment* outlines current understanding of and road maps for marine-based geoengineering. This is defined under the London Convention and Protocol as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long lasting or severe".[1]

This chapter takes a broad remit, including marine-based: CO_2 removal (CDR), defined as "human activity that captures CO_2 from the atmosphere and stores it for decades to millennia" (Smith and others, 2024); solar radiation modification (SRM); and structural engineering. Some countries are of the view that a cautious approach to SRM technologies is needed, as they carry numerous risks, not only for the environment but also with regard to geopolitical and security concerns.

Further reading on this subject can be found in the following documents:

- "The state of the science for marine carbon dioxide removal (mCDR) – a scientific summary for policymakers" (GESAMP, 2025)[2]
- *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (NASEM, 2022)[3]
- *Principles for Responsible and Effective Marine Carbon Dioxide Removal Development and Governance* (Doney and others, 2025)[4]
- Ocean Visions high-level road map (Ocean Visions, 2023)[5]
- *Strategy for NOAA Carbon Dioxide Removal Research* (Cross and others, 2023)[6]
- *Guide to Best Practices in Ocean Alkalinity Enhancement Research* (Oschlies and others, 2023b)[7]
- A code of conduct for marine carbon dioxide removal research programme (Boettcher and others, 2023)[8]
- The State of Carbon Dioxide Removal (Smith and others, 2024).[9]

The Paris Agreement (2015) sets a goal of limiting temperature increases to "well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels", which will require rapid, deep and sustained greenhouse gas reductions and ultimately the attainment of net-zero CO_2 emissions by mid-century (IPCC, 2018; UNFCCC, 2023). A significant gap remains between international targets and the actions required to limit the extent of warming to 1.5°C (IPCC, 2023). All scenarios and action pathways that lead to achievement of the Paris goal require global net negative emissions, whereby the greenhouse gases taken up by land and ocean exceed the amount released to the atmosphere (Schipper and others, 2022). One proposed pathway for achieving this is the implementation of geoengineering approaches to counterbalance residual or harder-to-abate emissions (Pathak and others, 2022; IPCC, 2023) and their impact on global warming. That said, methodologies remain unproven in practice, requiring significant research abiding by the precautionary approach (Cooley and others, 2023). Furthermore, there is considerable debate around the definition and quantification of residual emissions (Buck and others, 2023).

The range of biological, chemical and physical processes that influence air-sea CO_2 exchange (see subsect. 5B, chap. 1) suggest that it may be possible to enhance the rate and capacity for ocean carbon storage through methods such as the implementation of mCDR techniques (NASEM, 2021) (see figure I). Some mCDR methods seek to enhance the diffusion of atmospheric CO_2 into seawater by increasing the production and/or

1 Resolution LP.4(8) (not in force), available at www.imo.org/en/knowledgecentre/indexofimoresolutions/pages/ldc-lc-lp.aspx.
2 Available at https://oceanrep.geomar.de/id/eprint/62361/.
3 Available at www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration.
4 https://oceanpanel.org/wp-content/uploads/2025/06/OP_mCDR_Blue-Paper-1.pdf.
5 https://oceanvisions.org/wp-content/uploads/2023/10/A-Comprehensive-Program-to-Prove-or-Disprove-Marine-Carbon-Dioxide-Removal-Technologies-by-2030_FINAL.pdf.
6 https://sciencecouncil.noaa.gov/wp-content/uploads/2023/06/mCDR-glossy-final.pdf.
7 https://sp.copernicus.org/articles/sp-oae2023-full-report.pdf.
8 Available at www.aspeninstitute.org/publications/a-code-of-conduct-for-marine-carbon-dioxide-removal-research/.
9 www.stateofcdr.org/.

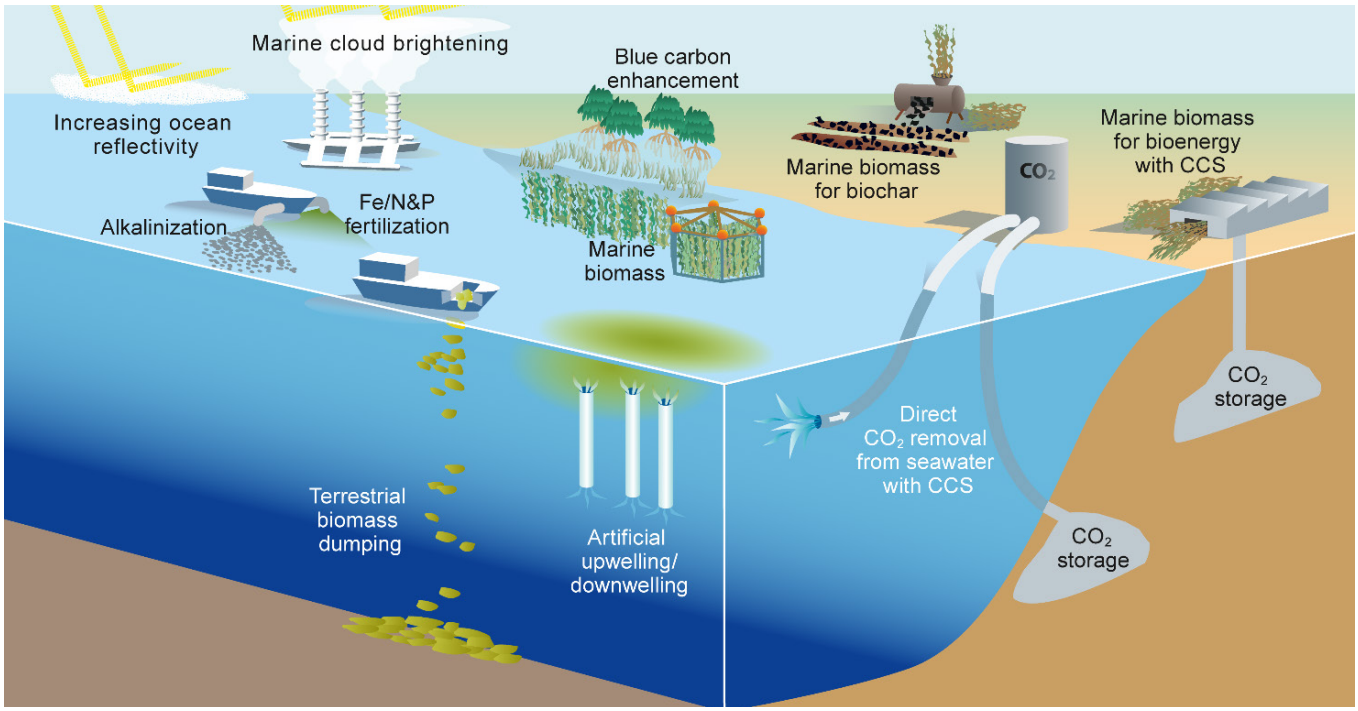
storage of organic carbon or by altering the inorganic pool of dissolved carbon. Biological mCDR techniques, including direct nutrient addition or upwelling of nutrient-rich waters to encourage primary production and the restoration of coastal vegetated ecosystems, potentially stimulate the conversion of dissolved CO_2 into plant matter through photosynthesis. Permanent or long-term removal requires the export or burial of the carbon such that its release back into the atmosphere following degradation is prevented. Deposition of terrestrial and marine biomass into the deep ocean for long-term storage is also proposed. Chemical mCDR approaches propose enhancing the capacity of the ocean to absorb atmospheric CO_2 either by increasing alkalinity, which forces the conversion of dissolved CO_2 into the more stable compounds (carbonate and bicarbonate ions), or by electrochemically removing the dissolved CO_2 for geological storage. In both cases the perturbations in seawater chemistry are designed to create an air-to-sea gradient that drives the absorption of more atmospheric CO_2 into the ocean. Physical mCDR approaches, including the downwelling of carbon-enriched surface waters, have also been suggested (GESAMP, 2025).

Ultimately, the successful long-term storage of CO_2 sequestered by CDR depends on either its incorporation into stable biogeochemical compounds in the ocean and ultimate burial in deep sediments (e.g. Boyd and others, 2024) or CO_2 capture and geological storage, which offers the most certainty for permanent CO_2 removal (IPCC, 2023). The placement of CO_2 saturated fluids on the deep seabed for long-term storage has also been considered (IPCC, 2005), as has the deposition of terrestrial biomass (Levin and others, 2023). All of the techniques have uncertain ecological impacts, long-term stability and legality.

Structural geoengineering techniques include the adoption of low-carbon manufactured building products and the design of marine structures to enhance biodiversity (UNEP, 2023; Fennel and others, 2021; Dafforn and others, 2015; Firth and others, 2024). Such approaches may be relevant as coastal development (including for mCDR) progresses (see subsect. 5A, chap. 9).

Marine SRM approaches seek to explore increasing the albedo of the atmosphere or the ocean's surface, enabling more energy to be reflected away. Techniques include seawater sprays to stimulate cloud formation, sea-ice enhancement, microbubbles and reflective foams (e.g. GESAMP, 2019); figure I). Ocean heat displacement and the use of more sustainable or biobased materials in ocean engineering have also been proposed as mechanisms for supporting decarbonization through the production of renewable electricity and CO_2 emission reduction during construction (GESAMP, 2019; NRC, 2006).

Figure I
Solar radiation modification and mCDR approaches



Source: Artwork, Rita Erven, Helmholtz Centre for Ocean Research Kiel (GEOMAR), Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0).

Although the fundamental scientific principles of geoengineering approaches are well known, their technological maturity, environmental impact and potential for wide-scale implementation vary significantly (see figure II). Several recent synthesis reports outline the challenges and research gaps (see above), and while there is debate, the current consensus is that most of the techniques are not yet proven effective, safe or technologically mature enough to scale. Correspondingly, the level of investment in marine-based techniques remains considerably lower than terrestrial alternatives such as direct capture, bioenergy with CCS (BECCS) and biochar (Smith and others, 2024). Notwithstanding the London Protocol (see below), there are no binding international agreements that comprehensively and specifically address mCDR (Webb and others, 2023). Controlled pilot studies are starting to address some of the critical knowledge gaps in these approaches. GESAMP (2024) currently identifies more than 39 mCDR initiatives aimed at sequestering carbon in the marine environment. Of these, the most numerous are macroalgae farming, ocean alkalinity enhancement, biomass sinking and ocean fertilization (28%, 20%, 18% and 15%, respectively). Crop wastes feature strongly in the biomass disposal category, alongside sargassum, accounting for a further four of the macroalgae farming initiatives. The development of monitoring, reporting and verification (MRV) protocols that assess carbon storage, while accounting for local-to-global-scale marine processes, is another recognized research priority. Additional uncertainties regarding inter alia environmental impacts, resource use, societal acceptability and economic viability of marine geoengineering and mCDR approaches will need to be adequately addressed, with effective governance frameworks implemented, before considering deployment at climatically relevant scales. This chapter outlines the current challenges and priorities for marine geoengineering, including mitigation potential, environmental effects, impacts on communities, economic feasibility, governance and pathways for ensuring sustainable development.

Figure II

Status of mCDR and other marine geoengineering approaches and the potential changes

Geoengineering category		Method	Carbon storage pool	Storage time-scale	Readiness	Mitigation potential	Location	Spatial interactions with other ocean users	Potential for natural system feedbacks
Biological mCDR	Ecosystem restoration	via mangrove / saltmarsh / seagrass restoration	biota	short <100 yr	medium TRL 5–6 demonstration	small <3 $GTCO_2$/yr	mostly coastal	likely >66%	likely >66%
		via marine aquaculture							
	Macroalgae growth	with deposition in deep marine	sediments	medium 100–1000 yr		large >9 $GTCO_2$/yr	coastal		
		with deposition in anoxic basins							
		with deposition on land	soils						
	Microalgae growth / Fertilisation	via macronutrient addition / upwelling	sediments			moderate 3–9 $GTCO_2$/yr	oceanic	likely as not 33–66%	
		via micro nutrient addition							
	Terrestrial biomass	deposition of terrestrial carbon at sea							
Chemical mCDR	Direct ocean capture with CCS	via electrolysis	geological	long >1000 yr	low TRL ≤4 research and development	large >9 $GTCO_2$/yr	coastal	unlikely <33%	unlikely <33%
		via electrodialysis							
	Ocean alkalinity enhancement	via silicate mineral weathering	minerals				oceanic	likely as not 33–66%	likely as not 33–66%
		via ocean liming							
		via dissolution of limestone and other carbonates							
		ocean crust mineralisation	geological						
Physical mCDR		artificial downwelling		short			mostly oceanic	likely >66%	likely >66%
Solar radiation management	Oceanic and Atmospheric albedo	via enhanced sea ice formation	N/A	N/A		N/A			
		via microbubbles							
		via reflective foam and other materials							
		via marine cloud brightening							
Structural	Zero carbon	use of low carbon / biomaterials in ocean engineering	construction	short <100 yr					
	Habitat	structures to enhance ecosystems	biota		medium				

Sources: Based on Smith and others, 2024; and Cooley and others, 2023.

Note: Blank spaces indicate a lack of data.

2. Pressures and impacts

Chemical mCDR approaches

It is contended that chemical mCDR methods that increase the pH and/or alkalinity of seawater (either through mineral addition or electrochemical methods) have significant long-term carbon sequestration potential (NASEM, 2022; Kwiatkowski and others, 2023; Oschlies and others, 2023a; Palmiéri and Yool, 2024; see also subsect. 5B, chap. 3). However, complex multiscale ocean mixing processes, and the long timescales required for CO_2 diffusion into seawater (Jones and others, 2014), create significant uncertainty for their potential efficacy. Oceanic uptake of CO_2 might decrease in the future as a consequence of progressing ocean warming (enhancing outgassing), continuing ocean acidification (decreasing oceans' storage capacity) as well as potentially reduced CO_2 emissions due to successful climate policy (Gruber and others, 2023). Furthermore, any alteration to marine chemistry resulting in increased carbon storage will impose chemical gradients that exceed normal variability. Reducing these gradients by spreading operations over larger areas will have implications for both cost and monitoring and for the social acceptability of mCDR projects (Satterfield and others, 2023). Increasing seawater pH and alkalinity may not linearly enhance carbon storage. At a higher pH, bicarbonate saturation can reach a tipping point, reducing the efficiency of further CO_2 uptake and potentially leading to diminished or even negative effects on carbon drawdown (Suitner and others, 2024).

A large body of research describes ecosystem impacts arising from increasing levels of CO_2 leading to ocean acidification (Doney and others, 2020). Conversely, little work to date has looked at the ecological effects of increased alkalinity. Subhas and others (2022) and Ferderer and others (2022) both noted limited impacts on plankton communities during small-scale microcosm experiments but highlight the need for further research (Bach and others, 2024).

Estimates of chemical mCDR potential have been reported in the range of 3 $GtCO_2\ yr^{-1}$–30 $GtCO_2\ yr^{-1}$ (Köhler and others, 2013; Renforth and Henderson, 2017; Feng and others, 2017), but current pilots operate at the scale of tons. CDR activities would need to increase in both number and capacity by orders of magnitude, accompanied by increased environmental impacts and process uncertainties, within a relatively short timescale (Ocean Visions, 2023; Boyd and others, 2024).

Apart from sequestration and impact potential, the scalability of chemical mCDR approaches will depend on the deployment location (open ocean or coastal), deployment strategy (e.g. choice of alkalinity source), delivery mechanism, infrastructure needs (e.g. ships, systems for electrochemical stripping) and feasibility, energy requirements, raw materials and contamination, collectively making a full life-cycle analysis imperative (Eisaman and others, 2023).

Biological mCDR approaches

The conservation and expansion of macroalgal coastal ecosystems – such as salt marshes (sect. 4, subchap. 5I), mangroves (sect. 4, subchap. 5H), seagrass meadows (sect. 4, subchap. 5G) and kelp forests (sect. 4, subchap. 4I) – protect biodiversity, stabilize coastal habitats and act as carbon sinks, with an estimated storage potential of less than 3 $GtCO_2\ yr^{-1}$ (UNFCCC Ocean Dialogue, 2023; Canadell and others, 2021; Erlania and others, 2023; Krause-Jensen and Duarte, 2016; Do Amaral Camara Lima and others, 2023; Yau and others, 2023).

Macroalgae aquaculture can potentially contribute to mCDR if it leads to long-term carbon storage but will compete with phytoplankton for nutrients (Berger and others, 2023). Alternatively, such aquaculture can contribute indirectly to reducing climate pressures through food and product provision, improving water quality (Krause and others, 2022; Duarte and others, 2022) and mitigating local ocean acidification and deoxygenation (Gao and others, 2022; Xiao and others, 2021; Dinghui Zou, 2005). Deposition on deep ocean sediments of harvested macroalgae, or terrestrial biomass, may significantly increase carbon sequestration and its climatic benefits (e.g. Wu and others, 2023), although the potential scalability and durability remain uncertain (Berger and others, 2023). Other post-harvest uses of macroalgae (feed additives to reduce ruminant methane emissions, biofuels and plastic substitutes) have additional climatic benefits (Kinley and others, 2020), while the removal and use of beach wrack for agricultural soil improvement can have a positive impact on carbon sink efficiency if done sustainably (Lanari and others, 2024). Crucially, impacts on habitats and populations stemming from the alteration of the ecosystem must be considered (Ross and others, 2023; Chopin and others, 2024; Hyndes and others, 2022). Deposition of shells from shellfish aquaculture has also been proposed as a mCDR technique by

restoring alkalinity, although the efficiency of the process has been questioned, and full life-cycle assessments are yet to be conducted (e.g. Boyd and others, 2024).

Microalgal mCDR methods are aimed at increasing primary productivity through fertilization using micronutrients, such as iron fertilization, or macronutrients (e.g. nitrogen, phosphorus) through the upwelling of deep nutrient-rich waters. Iron fertilization has been shown to promote the local growth of phytoplankton, particularly diatoms, but an increase in the amount of carbon that reaches the deep ocean is not generally observed (Boyd and others, 2007; Martin and others, 2013; Jiang and others, 2024). Iron fertilization may also lead to wide-scale changes in nutrient distribution, reduced interior oxygen concentrations and decreases in ecosystem biomass in the tropics with implications for fisheries (Tagliabue and others, 2023). Concerns such as these led Parties to the London Convention and London Protocol to issue a statement of concern in 2007 (IMO, 2007), leading to the adoption of a resolution in the following year that introduced the first international controls on ocean fertilization activities (IMO, 2007). Further research is needed, following the London Protocol 2013 guidelines for scientific research to better assess the efficacy, impacts and feasibility of this approach (Buesseler and others, 2024). Fertilization through the upwelling of nutrient-rich waters has been shown to have scalability constraints, with the CDR potential of the approach thought to be limited to 0.1 $GtCO_2\ y^{-1}$ (Koweek, 2022; Yool and others, 2009).

Physical mCDR approaches

Artificial downwelling has been proposed as a method to accelerate the sinking of carbon carrying biomass to the deep ocean, driven by pumps or increased salinity gradients (NASEM, 2022), with only regional tests conducted (Stigebrandt and others, 2015). Primarily proposed as a method by which to counter deep ocean hypoxia, impacts and efficacy in sequestering carbon are unknown. Impacts on local temperature, salinity and plankton communities can be envisaged, and model studies have suggested that downwelling is highly unlikely to be competitive (Zhou and Flynn, 2005).

Structural geoengineering

Traditionally, coastal and marine developments involve the construction of rigid infrastructures such as seawalls, piers, ports as well as wind farms and oil platforms. These constructions, although needed for a wide range of societal demands, have considerable environmental impacts, including habitat loss. The production of building materials also generates carbon emissions (Fennel and others, 2021).

Geoengineering approaches can be applied in this context to promote low-carbon sustainable development practices aimed at mitigating environmental impacts from both existing and new marine infrastructure. Biobased materials are emerging as a solution for decarbonization through the responsible management of carbon cycles, with the potential for reducing construction-related emissions by up to 40% by 2060 (UNEP, 2023; Fennell and others, 2021). This approach involves using alternative raw materials, cement chemistries and fuels in the production process. Other approaches, such as eco-engineering, may also be viable alternatives, through the design of structures to promote the colonization of carbon-capturing organisms (Dafforn and others, 2015; Firth and others, 2024).

Implementing a large-scale transition to circular and biobased materials in the built environment involves significant risks. Without careful planning, decarbonization can lead to unintended ecological impacts, if biobased materials are not sourced sustainably (UNEP, 2023). In addition, it can worsen unfair labour practices and result in uneven economic shifts during industry transitions (Lehne and Preston, 2018).

Solar radiation modification in marine environments

Unlike CDR approaches which reduce atmospheric CO_2, the root cause of warming, SRM works by reflecting incoming solar radiation, purporting to cause a cooling effect (MacMartin and others, 2018). While theoretically effective, there is potential to generate adverse impacts on climate, weather, ecosystems and air quality with geopolitical implications (Jones and others, 2013, 2018; NASEM, 2021; UNEP, 2023; Mengis and others, 2016). From an ocean perspective, changing the heat and light reaching the surface ocean may alter ecosystems by changing hydrodynamics, nutrient supply to the photic zone and photosynthetically available radiation. The effect on carbon cycles is highly uncertain (Cao, 2018; Zarnetske and others, 2021). Consequently, at present, SRM is a controversial approach, with no international consensus on research pathways (UNEP, 2023) or successful calls to establish international scientific review and governance processes to ensure an equitable, transparent and rigorous body of knowledge (UNEP, 2023).

Monitoring, reporting and verification

An acute challenge for geoengineering is establishing protocols that deliver sufficient knowledge into the efficacy and impact potential of each method and generate trust in regulators, publics and markets (e.g. Ho and others, 2023; Boyd and others, 2023). The time and spatial scales over which geoengineering interventions may be realized complicate such protocols, and the potential lag between mCDR implementation and carbon drawdown presents a challenge for financing.

Joint model and observation approaches to MRV for mCDR are recommended (Fennel and others, 2023), so that predictive models can establish the likelihood of success of a given intervention, while being appraised by observations. However, models have inherent uncertainties, which cannot be completely resolved by cost-limited observations, suggesting that complete certainty will be elusive (Bach and others, 2023) and the risks must be carefully considered in advance of any trials.

From an observational perspective, environmental sensors and their deployment options (e.g. autonomous platforms such as Biogeochemical Argo floats, gliders and drones) are generally well established (e.g. Yin and others, 2021; Lichtschlag and others, 2021). However, their capability for measuring key parameters for conducting market- and regulatory-acceptable MRV at and beyond initial deployment locations is yet to be proven. Similarly, the financial costs and carbon emissions of at-sea monitoring are currently considered to be prohibitive for at-scale implementation and remain a focus of ongoing research activities.

Modelling capability among scientists is relatively well established, falling into two broad categories.

- High-resolution local- and regional-scale models, that address single or clusters of geoengineering/mCDR operations, assessing dispersal, ecosystem impact, local sequestration efficacy and advection to deep water (Khangaonkar and others, 2024).
- Global ocean or Earth system models that assess the long-term effectiveness of upscaled geoengineering /mCDR approaches, which consider the biotic and abiotic carbon cycles and macroscale hydrodynamics and operate on decadal to millennial scales (Oschlies and others, 2023b; Bach and others, 2023).

Lack of fully comprehensive biodiversity in standard marine models may restrict the ability to accurately simulate biological mCDR or specific impacts. While the marine carbonate system is well understood, care must be taken that the chemical parameterizations still hold for mCDR interventions and are applied in both observational and modelling studies (Dupont and Metian, 2023; Schulz and others, 2023).

MRV for mCDR is a rapidly growing area of research drawing on natural analogues (Subhas and others, 2023) and small-scale field trials (Cyronak and others, 2023). Decision-support tools (Chay and others, 2022) also provide high-level frameworks with which to indicate confidence levels for various approaches, although the status of current certification practices remains complex, diverse and inconsistent (Arcusa and Sprenkle-Hyppolite, 2022). By contrast, protocol development for SRM is in its infancy.

3. Socioeconomic considerations

Societal perceptions

Public attitudes towards mCDR and geoengineering are divergent (Jebari and others, 2021). On the one hand, there is theoretical support for strategies to reduce CO_2. On the other, opposition emerges when specific projects are proposed, owing to uncertainties about their risks and reversibility, as well as governance shortcomings (Cox and others, 2022). This tension is further compounded by the divide between "natural" and "engineered" solutions, as public perceptions are heavily influenced by how technologies are framed (Bertram and Merk, 2020).

Conditional supporters favour mCDR technologies, but their acceptance is typically contingent on the perception of co-benefits, controllability and alignment with conservation efforts (Bertram and Merk, 2020). For example, in countries such as the United States, Canada and the United Kingdom, where prior knowledge of CDR remains very low, public support can waver depending on actual or perceived risks and benefits (Cox and others, 2020). This type of support is particularly evident in responses to different approaches: ecosystem-based solutions, such as blue carbon management, tend to receive more public support, while engineered methods such as ocean fertilization face significant resistance (Jinnah and others, 2021).

Less controversial approaches which align with traditional conservation methods, such as wetland restoration

and algal farming, tend to receive general (or unconditional) support. Acceptability follows from perceived co-benefits, for example food security and enhanced biodiversity (Were and others, 2019). These nature-based solutions are preferred globally, especially where local livelihoods are intertwined with ecosystems (Bertram and Merk, 2020). However, even supporters of climate mitigation express concerns about the potential social, economic or environmental impacts. These concerns grow when interventions appear intrusive or large scale, particularly with engineered solutions such as ocean alkalinity enhancement (Bertram and Merk, 2020).

In the global North, concerns are often centred around environmental risk and governance, with public preference leaning towards small, localized projects (Bertram and Merk, 2020; Baum and others, 2024).

In the global South, large-scale projects intended to offset emissions in the global North often raise ethical issues regarding land use and sovereignty (Zeng and others, 2021; Hickel and Slamersak, 2022). Concerns about exploitation and inequity in the global South are further fuelled by fears of wealthier nations' reliance on technological fixes rather than reducing their emissions at the source (Jinnah and others, 2021). This amplifies opposition in areas where the risks associated with new technologies are perceived as disproportionately impacting poorer nations (Satterfield and others, 2023). This resistance to mCDR projects is not confined to one region but is observed globally, reflecting a scepticism towards interventions considered disruptive or overly risky.

Also significantly influencing public acceptance of mCDR is the perceived urgency of climate change (Bellamy, 2022). Openness towards mCDR does not equate to uncritical acceptance. Comfort with specific technologies varies depending on perceived risks and uncertainties. While solutions such as coastal restoration and direct air capture tend to be more favoured, experimental technologies such as ocean fertilization and ocean alkalinity enhancement face greater scepticism, largely owing to concerns about environmental impacts and the permanence of carbon storage (Cox and others, 2024; Nawaz and others, 2023). Generally public support for geoengineering techniques such as SRM is lower than those for mCDR, with concerns about controllability, reversibility and a preference for mitigation techniques over temperature management (NASEM, 2021). These disparities reflect how risks and uncertainties associated with those technologies, as well as climate vulnerability, inequity and development priorities, shape regional attitudes towards climate intervention technologies.

Economic potential and sustainability

The economic potential of geoengineering depends on integration into carbon markets, providing financial incentives and fostering new industries. The co-benefits from certain mCDR techniques could include supporting sectors such as tourism and fisheries, contributing to a "blue growth" strategy. This is the case notably for ecosystems restoration.

However, integrating CDR into markets entails significant risks. A primary concern is mitigation deterrence, where reliance on credits substitutes for, rather than complements, emission reductions (Trencher and others, 2024). Neglecting the mitigation hierarchy – whereby emission avoidance and reduction should precede reliance on removals – risks fostering overreliance on market mechanisms and delaying decarbonization (Caldecott and Johnstone, 2024).

Further risks concern the environmental and social integrity of carbon markets, including challenges such as the risk of low-quality credits misrepresenting actual emission reductions (Trencher and others, 2024). On the supply side, challenges include ensuring additionality, permanence, accurate monitoring, avoidance of double counting and independent verification (Kreibich and Hermwille, 2021). On the demand side, credible claims and protections against greenwashing are essential (Trencher and others, 2024). Without double-claiming prevention, the voluntary carbon market (VCM) may struggle to encourage genuine mitigation efforts. Accurate MRV is essential for maintaining market credibility, as inadequate MRV creates uncertainties about the actual carbon removal achieved. As environmental conditions change, it becomes challenging to assess the true impact of CDR projects, leading to credits that may not accurately reflect real carbon removal. Issues of additionality also arise when projects receive credits for carbon removal that would have happened without market incentives (Betz and others, 2022).

The VCM, provided that solid guardrails are established, such as those established in the standards and methodologies of the Paris Agreement Crediting Mechanism, could provide a valuable means for financing climate action and sustainable development, especially for projects in vulnerable areas. Smaller-scale projects such as the Mikoko Pamoja (mangrove restoration) project in Kenya,

funded through the VCM, offer a promising opportunity for small island developing States (Kairo and others, 2018), although the VCM for projects in developing States is more suited to ecosystem restoration, as opposed to other geoengineering approaches such as ocean alkalinity enhancement or ocean fertilization. This approach can be especially effective when combined with organic certification in areas with existing aquaculture, generating revenue through carbon credits, supporting local livelihoods and community development.

To tackle challenges of accurately measuring carbon sequestration within restoration (Macreadie and others, 2019), regional and international networks such as the Blue Forests Project,[10] the Blue Planet fund[11] and the Blue Carbon Initiative,[12] are developing best practices to effectively utilize international carbon finance (OECD, 2020), although this currently applies to habitat restoration rather than geoengineering.

Overall (i.e. not mCDR specific), carbon credit issuances are currently increasing exponentially (37 million tons CO_2 by July 2025[13]), while retirements of carbon credits have plateaued (Sylvera, 2024). The economic feasibility of the carbon market hinges on developing MRV capacity and a combination of technical readiness, storage verification, supportive policies and strategies to mitigate carbon leakage (emissions reductions in one region that lead to increased emissions elsewhere; Schroeder and Stracca, 2023), while maintaining industry competitiveness (IFC, 2023).

Generally, the global carbon market is bolstered by policies and mechanisms facilitating emissions reductions and promoting sustainable investment (IFC, 2023). Carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems such as the European Union Emissions Trading System, incentivize companies to reduce emissions. The idea of integrating carbon removals into the European Union Emissions Trading System is gaining traction (Meyer-Ohlendorf, 2023).

Supportive policies are applied to encourage market participation. On 10 April 2024, the European Parliament approved the Carbon Removals and Carbon Farming (CRCF) Regulation,[14] creating the first European Union-wide framework for certifying carbon removals, carbon farming and carbon storage. It sets quality standards, tackles greenwashing and promotes investment in carbon removal technologies and sustainable farming to support the European Union's climate goals.

Various levels of implementation for sustainable ocean-based economy programmes, including established official development assistance, involve key mechanisms such as conservation trust funds, blue carbon payments and private sector concessions. Improving practices that facilitate carbon sequestration by ocean ecosystems offers economic opportunities through emerging blue carbon markets. These activities require a robust framework for successful carbon investing, including precise measurement and verification (World Bank, 2023).

4. Sector-relevant governance

Governance of marine geoengineering and CDR spans international, regional and domestic frameworks. Currently, there are no binding international laws specifically governing marine geoengineering or CDR, but various general international agreements and rules of customary international law may apply (e.g. United Nations Convention on the Law of the Sea; International Tribunal for the Law of the Sea, advisory opinion on climate change and international law, 2024; International Court of Justice, advisory opinion on the obligations of States in respect of climate change, 2025) (see also sect. 3). Non-binding instruments, including a 2010 resolution of the Parties to the Convention on Biological Diversity, which applies to geoengineering broadly (e.g. decision X/33 (2010)) and widely agreed conventions have bridged regions (e.g. International Law Commission, Prevention of Transboundary Harm from Hazardous Activities;[15] Oxford Principles on Geoengineering[16]).

10 https://gefblueforests.org/.
11 https://icai.independent.gov.uk/html-version/blue-planet-fund-review/.
12 www.thebluecarboninitiative.org/.
13 www.cdr.fyi/.
14 www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/ENVI/DV/2024/03-11/Item9-Provisionalagreement-CFCR_2022-0394COD_EN.pdf.
15 https://legal.un.org/ilc/texts/instruments/english/draft_articles/9_7_2001.pdf.
16 www.oxfordmartin.ox.ac.uk/geoengineering.

Marine geoengineering could implicate various provisions of the United Nations Convention on the Law of the Sea,[17] including those governing marine scientific research and protection of the marine environment, particularly as marine scientific research has been interpreted as encompassing marine geoengineering research (Brent and others, 2019; Webb and others, 2023). Under articles 192 and 194 (1), the Convention includes an obligation to protect the marine environment by taking all measures "necessary to prevent, reduce and control" marine pollution. Other provisions include the obligation not to transform one type of pollution into another (United Nations Convention on the Law of the Sea, art. 195; International Tribunal for the Law of the Sea, advisory opinion, 2024). This has some implications for geoengineering both directly in association with the introduction of substances or energy into the ocean (Boyle and Ghaleigh, 2016; Reynolds and Wagner, 2018; Webb and others, 2023) and also indirectly through its application to reduce greenhouse gas emissions. In its advisory opinion, the International Tribunal on the Law of the Sea determined that greenhouse gas emissions into the atmosphere constitute marine pollution and thus States have an obligation to reduce emissions under the Convention.

The modernizing London Protocol, an extension to the London Convention (1972), entered into force in 2006 but has not been ratified by all Convention Parties, and thus the two instruments continue to operate jointly. While the Convention is generally more permissive of dumping of wastes, the Protocol takes a more precautionary approach, prohibiting the dumping of all wastes and other matter, except those on the "reverse list" in annex 1. In 2006, CO_2 was added to annex 1 to the Protocol, thereby enabling sub-seabed carbon storage, subject to purity standards and risk assessment procedures, amended in 2009 to allow export of CO_2 to other countries for storage. The amendment is yet to enter into force but has been provisionally applied since 2019. Furthermore, in 2012, the governing bodies for the Convention and Protocol adopted specific guidelines for the assessment of carbon dioxide for disposal into sub-seabed geological formations (LC 34/15, annex 8) to guide its implementation. These instruments have implications for some forms of mCDR.

In 2008, the Parties to the London Convention and Protocol adopted a non-binding resolution on ocean fertilization, declaring that "ocean fertilization activities other than legitimate scientific research should not be allowed" (resolution LC-LP.1, adopted on 31 October 2008). In 2010, the Parties adopted an assessment framework for evaluating proposed scientific research projects, requiring (among other things) ex ante environmental review and ongoing monitoring and management of risks (resolution LC-LP.2, adopted on 14 October 2010). This approach to ocean fertilization of permitting some legitimate scientific research but restricting commercial deployment was codified in a formal amendment to the London Protocol in 2013 (resolution LP 4(8), adopted on 18 October 2013). The amendment is yet to enter into force but is intended to establish a governance framework for certain marine geoengineering and CDR activities listed in a new annex 4 (Röschel and Neumann, 2023). Currently, only ocean fertilization is listed.

In 2022, Parties to both the London Convention and the London Protocol committed to evaluating four marine geoengineering techniques – ocean alkalinity enhancement, biomass cultivation for carbon removal, marine cloud brightening and surface albedo enhancement – for potential listing under the 2013 amendment (London Convention, 2022). While that process remains ongoing, in 2025, the Parties issued a statement on marine geoengineering.[18]

The United Nations Framework Convention on Climate Change (UNFCCC, 1992) does not contain explicit references to geoengineering. It contains references to "removal by sinks", language repeated in the Paris Agreement (UNFCCC, 2015). The Convention defines "sink" as "any process, activity or mechanism which removes a greenhouse gas ... from the atmosphere" (UNFCCC, 1992). The recognition of the ocean's critical role in climate action under the Convention has evolved significantly over time.

While yet to enter into force, the 2023 Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction[19] may have implications for marine geoengineering and CDR

17 www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

18 See the summary of the forty-seventh Consultative Meeting of Contracting Parties to the London Convention and the twentieth Meeting of Contracting Parties to the London Protocol (LC 47/LP 20), available at www.imo.org/en/mediacentre/meetingsummaries/pages/lc-47-lp-20.aspx.

19 See www.un.org/bbnjagreement/en.

activities. For example, Part III outlines a framework for establishing area-based management tools, and Part IV outlines detailed environmental assessment requirements, which could be used to control where and how marine activities are conducted (Webb, 2024).

In addition, potentially relevant to marine geoengineering and CDR are international agreements governing shipping, such as the International Convention for the Prevention of Pollution from Ships Convention),[20] global human rights conventions and regional seas conventions including the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)[21] and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention),[22] the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention)[23] and the Convention on the Protection of the Black Sea Against Pollution (Bucharest Convention).[24]

Emerging domestic governance frameworks

To date, decisions relating to CDR and other marine geoengineering activities have often been regulated under domestic environmental laws, including (although not restricted to) laws enacted to implement the London Convention and Protocol and other international agreements; however, regulation varies significantly between countries (Silverman-Roati and Webb, 2023). For example, in the United States, the federal Marine Protection, Research, and Sanctuaries Act – i.e. the domestic law implementing the Convention – governs many marine activities. Other federal, state, tribal and local laws may also apply to some projects. The laws of a few countries allow research for marine geoengineering or CDR, subject to permitting and other requirements (Silverman-Roati and Webb, 2023). At least one other country, Australia, has taken steps to implement the 2013 London Protocol amendment revising its Environment Protection (Sea Dumping) Act 1981, but the revisions will not take effect until the London Protocol amendment enters into force.

By contrast, other countries have implemented regulation that is more restrictive than the 2013 London Protocol amendment. For example, in Germany, the High Seas Dumping Act prohibits any addition of substances to the ocean in connection with marine geoengineering and/or CDR, with only a limited exception for certain ocean fertilization research (Proelss and Steenkamp, 2023).

See also section 3 of the present *Assessment*.

5. Sustainability pathways

The ability of mCDR to make a meaningful contribution towards global targets is theoretically plausible but not yet established. Nevertheless, interest and efforts on the research and development of various techniques have accelerated significantly since the publication of the second *World Ocean Assessment*, delivering a rapidly evolving knowledge base. Generically, motivations and challenges identified are diverse and sometimes opposing, but may be broadly summarized as environmental, social, economic, regulatory and technical.

There can be potential co-benefits of certain macroalgal mCDR approaches, for example in protecting biodiversity, creating gender positive roles and providing food and other resources (Larson and others, 2021; Zhang and others, 2022). Development of macroalgae approaches for mCDR will require a sustainability framework that emphasizes the critical importance of environmental limits and constraints imposed by nature and ecological impacts (Boyd and others, 2023) and incorporates performance indicators, ensures societal acceptance and enables policymaking that takes into consideration marine space allocation and reduces regulatory barriers (Cordell and others, 2009; Krause-Jensen and Duarte, 2016; Herrero and others, 2021). Conversely, biological mCDR methods based on the stimulation of phytoplankton productivity are thought to offer fewer direct co-benefits and have greater potential for disruptive ecosystem feedbacks, by altering the magnitude and geography of marine primary production (Tagliabue and others, 2023).

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20 www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.
21 www.ospar.org/convention.
22 https://helcom.fi/about-us/convention/.
23 www.unep.org/unepmap/who-we-are/barcelona-convention-and-protocols.
24 www.blackseacommission.org/Official%20Documents/The%20Convention/Overview/.

Concentrating mCDR deployments in designated offshore marine areas could provide infrastructural, economic and environmental benefits through a multi-use approach (Schupp and others, 2019) reducing user conflicts. Seaweed farming, for instance, adapted to local conservation targets can contribute to the goals of marine protected areas (MPAs), all while providing jobs and revenue to local communities (Le Gouvello and others, 2017).

Table
Motivations and challenges derived from the United Nations regional workshops

	Motivations	Challenges
Environmental	• Addressing climate change and the Paris Agreement goals • Reducing ocean acidification, greenhouse gas levels and emissions • Preserving marine ecosystems, biodiversity and ecosystem services • Sea-level change management • Understanding impacts of geoengineering on ecosystems • Nature-based solutions	• Life-cycle assessment, including lack of feasibility studies and post-implementation impact understanding • Potential for and lack of assessment of significant negative impacts, including technological limitations
Social	• Quality of life for future generations • Sustainable communities • Application of traditional knowledge	• Social licence to operate, awareness and education • Ethical and moral challenges – managing finite resources, who benefits and who pays, transnational impacts
Economic	• Limiting economic threats of climate change • Lowering cost of geoengineering/CDR and capacity-building	• Lack of incentive, financing and funding for capacity-building, especially in the least developed countries and small island developing States
Governance	• Development of regulations, legislation and policies • International cooperation and dissemination	• Lack of consistent policy, regulations, monitoring and standards • Interactions between landlocked and coastal States
Technical	• Technology development, innovation and excellence in research and development • Technology for exploration and sustainable exploitation of natural resources • Digital toolboxes to evaluate solutions	• Deep ocean exploration and monitoring

Source: Prepared by the writing team.

Several small-scale pilot studies assessing potential chemical mCDR approaches are currently in progress (Ocean Visions, 2024; GESAMP, 2024). Independent scientific oversight of these, in conjunction with the application of the London Protocol requirements, including the research assessment framework, as well as the proposed approaches to upscaling, will be crucial to maximize learnings in the next few years. Any move to upscale from pilot studies will require a full life-cycle assessment such that carbon emissions from energy, transport and installation are offset against carbon sequestered. As upscaled trials will span local and national jurisdictions to the open ocean, international coordination will be necessary to ensure that those experiments do not harm the environment and human societies.

There remains little consensus on testing, development, monitoring or regulation of SRM, with this controversial approach not considered as mitigation when the terminology of the Intergovernmental Panel on Climate Change (IPCC) is applied. Nevertheless, funding and

research and development are likely to increase in this sector over the coming years.

In summary, a number of uncertainties remain with regard to marine CDR and geoengineering techniques, including:

- Their impacts on marine ecosystems and coastal areas.
- Their effectiveness in the long-term removal and storage of CO_2, including ensuring that they do not reduce the ocean's natural CO_2 storage capacity.
- The energy and resources needed for deployment at scale and the effects on terrestrial ecosystems, including conflicts over, for example, minerals use and mining.
- There are currently no reliable technical means to monitor, report or verify the CO_2 that would be absorbed and sequestrated, especially considering the complexity and existing knowledge gaps about the ocean carbon cycle.

The key enablers for sustainable research progress are:

- Scientifically endorsed, standardized and accessible MRV approaches.
- Responsive and transparent funding mechanisms, ensuring that commercial interests do not influence the design, conduct and outcomes of the research activities.
- Collaboration and transparency for research will be required for geoengineering approaches to demonstrate feasibility (or lack thereof) and upscale effectively and safely if they are proven safe, effective and realistic.
- Global policy that prioritizes addressing knowledge gaps, equity concerns, risk perception and precautionary governance to strengthen understanding and control for mCDR and geoengineering research.



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Subsection 5B
One Health



Pedro Carillo

Introduction

One Health, defined by the One Health High-Level Expert Panel (OHHLEP and others, 2022) as an integrated, unified approach that is aimed at sustainably balancing and optimizing the health of people, animals and ecosystems, is a useful framework for identifying the linkages and interdependencies in socioecological systems that go beyond the human economic activities described in subsection 5A. This concept is based on several fundamental principles including equity, inclusivity, equal access, parity, socioecological equilibrium, stewardship and transdisciplinarity. The World Health Organization recognizes its particular relevance to food and water safety, nutrition, the control of zoonoses, pollution management and the combating of antimicrobial resistance.

Subsection 5B, One Health, of the third *World Ocean Assessment*, contains a consideration of issues with strong social dimensions such as human health and well-being, equity, gender and Indigenous, traditional owner and local community knowledge, in tandem with issues that have significant social impacts, such as the role of ecosystems in the carbon cycle, ocean hazards and the effects of the coronavirus disease (COVID-19) pandemic.

Marine ecosystems play a significant role in the capture, storage and sequestration of carbon and, therefore, on potential climate change mitigation (see subsect. 5B, chap. 1). Hence, the role of marine ecosystems in the carbon cycle is intrinsically related to ecosystem health (see sect. 4), the modulation that climate change exerts in maritime economic sectors (see subsect. 5B) and on global society, as detailed in the remaining chapters of the present subsection. The ocean also provides benefits for human health (see subsect. 5B, chap. 2), such as seafood, marine-derived pharmaceuticals or opportunities for exercise, and supports spiritual, cultural and recreational services, benefits for mental health or enhancement in social cohesion that contribute to better well-being (subsect. 5B, chap. 3). However, human activities are putting these benefits at risk through a diverse array of human pressures, such as climate change, coastal development and pollution.

The ocean is also a source of important natural hazards (see subsect. 5B, chap. 4), operating at different temporal scales and having different types of impacts. Minimizing these impacts requires different mitigation, adaptation and management measures, higher-level overarching governance, and institutional and social transformations.

The benefits obtained from the ocean, their deterioration by human activities, natural hazards and even the violation of human rights are unequally distributed across global society (see subsect. 5B, chap. 5). Inequality is facilitated by inadequate governance and decision-making processes that remain insufficiently participatory and inclusive, and with social equity, justice and human rights inadequately integrated. This unequal distribution of benefits and disbenefits is particularly conspicuous in the case of gender (see subsect. 5B, chap. 6), across sectors such as ocean science, fisheries and aquaculture, and for Indigenous and traditional local communities (see subsect. 5B, chap. 8).

The COVID-19 pandemic has affected people's relationship with the ocean, with some changes possibly becoming permanent. Furthermore, some consequences remain uncertain and underscored. The pandemic provoked high risks of infection and prolonged confinement periods in vessel crews. It also caused disruption to ocean research and observation. On the other hand, human pressures were temporarily reduced, benefiting marine ecosystems.

Lastly, Indigenous, traditional owner and local community knowledge is increasingly acknowledged as an alternative collective source of information complementary to non-Indigenous or classical scientific information. Indigenous, traditional owner and local community knowledge must be better integrated in governance processes and in future World Ocean Assessments.

Chapter 1
Role of ecosystems in the carbon cycle

Key points

- Covering approximately 71% of the Earth's surface, the open ocean contributes to approximately half of annual primary production, supporting approximately 80% of global animal biomass.
- The open ocean currently sequesters a similar amount of atmospheric carbon dioxide (CO_2) to that sequestered by the whole terrestrial biosphere, and the ocean has the capacity to store 40 times more CO_2 than the atmosphere.
- In coastal systems, coastal blue carbon ecosystems, such as seagrass, mangroves and salt marshes, are estimated to capture and store more carbon per unit area than terrestrial forests, meaning that, despite covering an area of less than 7 million km^2, coastal blue carbon ecosystems are considered globally important areas of carbon capture and storage, which contributes to their high economic and social value, together with other ecosystem services.
- Unvegetated, sea floor sediments on the continental shelf make up approximately 9% of the total marine area but hold the biggest carbon store in shelf systems, and more than 80% of organic carbon is buried in these subtidal sediments.
- The protection and restoration of coastal blue carbon ecosystems and shelf sediment seabed habitats will have significant benefits for both climate mitigation and biodiversity conservation.
- Continental shelf seas are a significant source of carbon (0.95 ± 0.25 Pg C y^{-1}) to the open ocean, although this transport is largely driven by physical and geochemical processes, rather than biological. However, horizontal carbon transport through the migration of animals is probably widespread, but largely unquantified.
- The value of carbon cycling ecosystems has been increasingly recognized, and many finance initiatives exist. However, blue carbon activities receive just 3% of total climate investment globally. This lack of financial support has been a barrier to bringing blue carbon conservation and restoration activities to scale.
- The recognition of the value of coastal blue carbon ecosystems in climate action has increased in recent years. However, at the time of publication, just over half (56%) of Parties to the United Nations Framework Convention on Climate Change have integrated coastal and marine nature-based solutions within new or updated nationally determined contributions as part of mitigation or adaptation measures.

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1. Introduction

While the vast majority of the carbon in the ocean is inorganic, and many of the processes that fix, transform and transport this carbon within and through the ocean are driven by physical or chemical processes (see sect. 4, chap. 3), there are also important biological processes that contribute to significant carbon cycling, and these are directly linked to the presence, function and health of marine ecosystems. Given that these same ecosystems also provide vital services to humans, including food provision (see subsect. 5A, chap. 1), understanding and protecting the role of ecosystems in driving the carbon cycle are intrinsically linked to the health (see subsect. 5B, chap. 2) and well-being of billions of people (see subsect. 5B, chap. 3). In this chapter, we will explore the role played by biological processes of key ecosystems in cycling carbon through the two main ocean systems: the open ocean (part 2); and the nearshore environment, comprising shelf, coastal, fjordic and estuarine systems (part 3). In part 4 of the present chapter, we will describe the transport pathways of carbon between the near shore and the open ocean. Lastly, we will consider the potential values of these ecosystems, and the carbon cycling processes that they provide, in the context of economic and non-economic valuation (part 5).

2. The open ocean

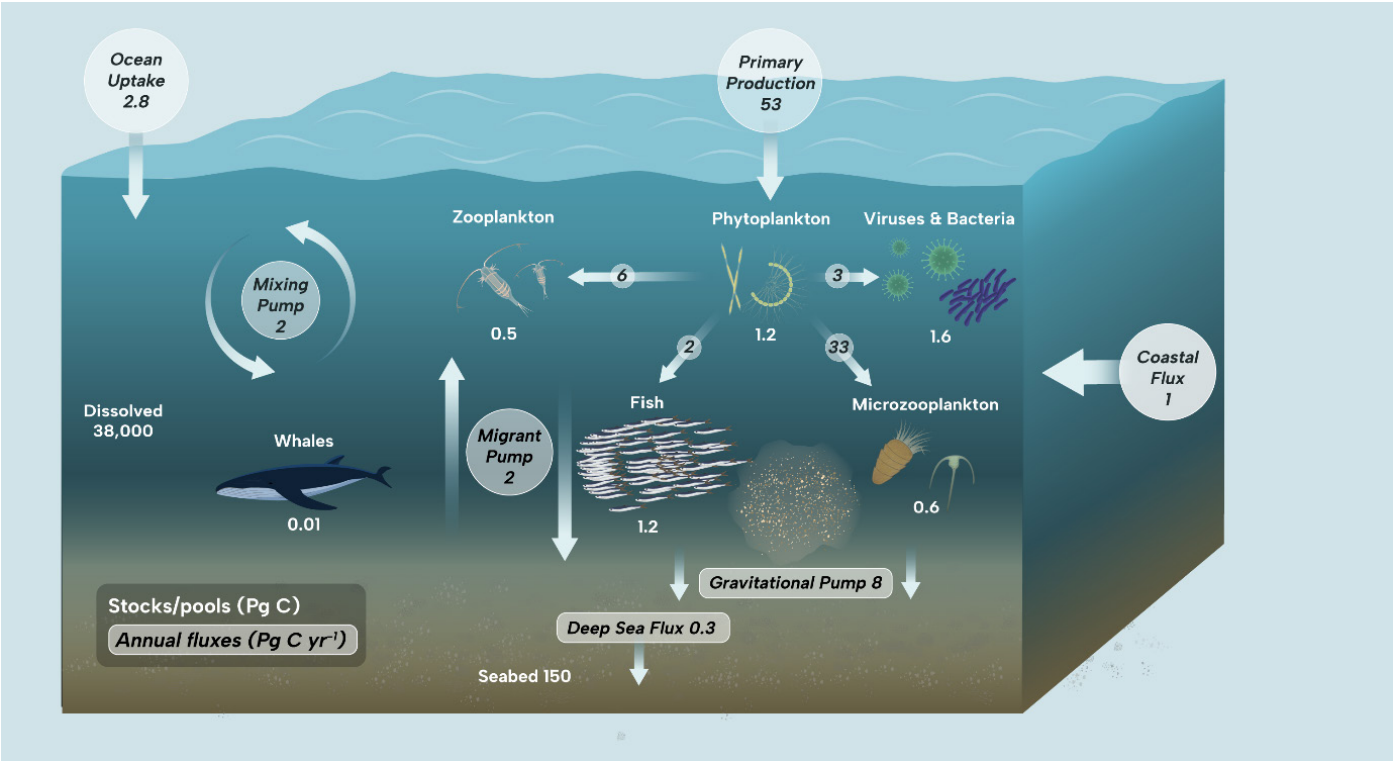
Carbon cycling in marine ecosystems

Accounting for approximately 71% of the Earth's surface, the open ocean contributes to approximately half of Earth's annual primary production (~49–56 Pg C yr^{-1}; Buitenhuis and others, 2013a; Kulk and others, 2020), despite much lower levels of photosynthetic biomass in the ocean (~0.5–2.4 Pg C) than on land (~450 Pg C) (Buitenhuis and others, 2013b; Bar-On and others, 2018). Primary production is dominated by microbial phytoplankton in the open ocean (Buitenhuis and others, 2013b; Bar-On and others, 2018), with lifespans ranging from a few days to weeks, leading to an inverted biomass pyramid from microbial primary producers at the base, up to higher trophic levels at the top, and a rapid turnover of photosynthetic biomass in the ocean (see figure I). In the wider context of the global carbon cycle, the marine biosphere represents a relatively small component; while marine biological (organic) carbon pools total approximately 5 Pg C, the ocean contains approximately 38,000 Pg C of dissolved inorganic carbon (DIC) and the atmosphere approximately 800 Pg C (see figure I; Friedlingstein and others, 2023). However, this relatively small amount of biomass, with significant fluxes between biological pools (see figure I), supports the life and productivity of the global ocean, the largest ecosystem (biome) on the planet.

Significant rates of primary production and rapid turnover allow the ocean to support approximately 80% of global animal biomass and approximately half of global protist biomass, which includes significant biomass from pelagic and mesopelagic fish (0.7–1.7 Pg C), large zooplankton (e.g. copepods, krill) (0.3–0.6 Pg C) and small microzooplankton, including protists such as ciliates and dinoflagellates (0.5–0.7 Pg C) (Buitenhuis and others, 2013b; Bar-On and others, 2018; Bar-On and Milo, 2019; Bianchi and others, 2021; Drago and others, 2022). While marine mammal biomass is roughly twice the size of wild terrestrial mammal biomass, it represents a low level of biomass overall (~0.007 Pg C), with baleen whales making up the majority (Greenspoon and others, 2023). Globally, marine mammal biomass is an order of magnitude smaller than the human population (0.065 Pg C) or domesticated mammal biomass (0.1 Pg C) (Bar-On and others, 2018; Greenspoon and others, 2023).

Carbon fixed into marine biomass through photosynthesis in the open ocean is rapidly consumed by pelagic organisms, with approximately 62% lost to ingestion and respiration by microzooplankton, approximately 12% directly to larger zooplankton and approximately 2% to 10% to viral lysis and infection (Calbert, 2001; Schmoker and others, 2013; Gao and others, 2022). Smaller proportions of primary production are lost directly, or indirectly through grazing on herbivorous zooplankton, to fish (<3%; Bianchi and others, 2021) and marine mammals. The remaining proportion of primary production (~18% or ~11 Pg C yr^{-1}) is lost from the upper ocean through the sinking of particulate material (i.e. cells, detritus), or the downward fluxes of dissolved organic material, or through the active migration of pelagic organisms from surface waters to depth (Boyd and others, 2019; Siegel and others, 2023).

Figure I
Open-ocean ecosystem roles in the carbon cycle



Sources: Bar-On and others, 2018; Boyd and others, 2019; Friedlingstein and others, 2023; Greenspoon and others, 2023; and Siegel and others, 2023.

Biological carbon pump(s)

While the open ocean lacks the immense plant biomass of land ecosystems, the ocean currently sequesters a similar amount of anthropogenic atmospheric CO_2 (~2.8 Pg C yr^{-1}) to that sequestered by the whole terrestrial biosphere (Friedlingstein and others, 2023), mainly through its physical circulation and geochemical characteristics (Sabine, 2021; see sect. 4, chap. 3), although open-ocean ecosystems also play a crucial role (Boyd and others, 2019; Siegel and others, 2023; Frenger and others, 2024). Marine photosynthesis draws CO_2 from the atmosphere into surface biomass, a portion of which enters the interior ocean through one of several transport pathways (see figure I), driving a gradient in CO_2 from the upper ocean into the deep sea through the collective action of ocean ecosystems, termed the biological carbon pump (Boyd and others, 2019; Siegel and others, 2023). While most of this material is typically broken down and respired by bacteria and zooplankton in the upper 1 km of the ocean, a small proportion of surface production (<2%) does reach the sea floor. So, although the biological carbon pump does not actually contribute much to the net ocean C sink, largely because its vertical fluxes (export) are balanced by the release of absorbed CO_2 (outgassing) from upwelled deep waters, it does maintain the long-term store of carbon in deep waters and sediments that would otherwise reside in the atmosphere (Frenger and others, 2024).

The timescale of ocean mixing is proportional to water depth. Some deep waters can be isolated from the atmosphere for up to approximately 1,000 years, while the upper ocean (<0.5 km) may exchange with the atmosphere seasonally, such as during winter mixing. The deeper a sinking particle reaches into the ocean the longer the carbon associated with that particle will be sequestered from the atmosphere. As a global average, particles sinking below 500 m are sequestered for 200 years or longer (Boyd and others, 2019), but this varies geographically depending on regional ocean circulation and mixing (Baker and others, 2024).

The breakdown and respiration of organic matter supplied to the ocean's interior through the biological carbon pump contribute to the ocean's capacity to store 40 times more CO_2 than the atmosphere (Friedlingstein and others, 2023; Frenger and others, 2024) and fuel deep sea bacteria and fauna at the sea floor. An even smaller

proportion (<1%) of surface production ends up sequestered into deep-sea sediments through the physical activity of organisms living at the sea floor. However, the vast area of the deep sea means that this small fraction of surface production makes up a large carbon stock that contributes significantly to C cycling and sequestration on millennial timescales (150–2,322 Pg C, depending on whether the upper 5 cm or 1 m is considered; Atwood and others, 2020), which is similar in size to that stored in terrestrial soils (1,700 Pg C) or permafrost (1,400 Pg C) (Friedlingstein and others, 2023).

Sinking particulate organic carbon (POC) falls as cells and detrital material, often aggregated into particles termed "marine snow" or packaged by large zooplankton as faecal pellets, and contributes to the "gravitational pump" which is responsible for ~80% of the approximately 11 Pg C annually exported by the biological carbon pump (Boyd and others, 2019; Siegel and others, 2023). Often these sinking particles still hold nutrients usable by heterotrophs, and it is now recognized that zooplankton often fragment these sinking particles into smaller particles that slow their descent, keeping them in the upper ocean longer (Mayor and others, 2014). This strategy has been termed "microbial gardening" where zooplankton promote bacterial and protist growth on fragmented particles before consuming the enriched microbial biomass (Mayor and others, 2014), which is more nutritious than the original sinking material (Cavan and others, 2020). This highlights the intricate ecological interactions involved in regulating carbon flow into the deep ocean.

Dissolved organic carbon (DOC), varying in form from simple metabolites such as polysaccharides and proteins to complex reworked molecules such as fulvic and humic acids, is an important component of the ocean's dissolved carbon pool (Friedlingstein and others, 2023) with microbial utilization of this pool as a carbon and nutrient source, responsible for breaking down the labile fractions of this material (Hansell, 2013; Jiao and others, 2014; Legendre and others, 2015). This "microbial carbon pump" recycles carbon and nutrients from the dissolved pool, but also changes the nature of the pool to a more refractory one which contributes to long-term carbon sequestration, lasting from hundreds to thousands of years (Hansell, 2013; Jiao and others, 2024; Legendre and others, 2015). Viral infection also plays a role in the microbial carbon pump, with viral lysis of infected plankton in the upper ocean providing a "viral shunt" retaining carbon near the surface, where it is broken down by microbes (Suttle, 2007; Kranzler and others, 2019). Recent research shows that some viral infections do not cause immediate cell lysis. Instead, metabolically inactive infected cells may sink, creating a "viral shuttle" that transports organic material to the deep ocean (Kranzler and others, 2021; Poulton, 2021).

The remaining carbon exported through the biological carbon pump is pumped to depth through two distinct mechanisms, one related to the physical mixing of the water column ("mixing pump") and the other related to vertical migration by zooplankton and nekton ("migrant pump") (Boyd and others, 2019; Siegel and others, 2023). The "mixing pump" involves various oceanographic processes that transport surface water into the ocean's interior, and any dissolved and particulate carbon contained in this water thereby becomes sequestered in the deep ocean. The volume of water, and the depth to which it is transported, varies seasonally and geographically.

Many organisms in the ocean go through daily or seasonal migrations from surface waters into the ocean's interior, either driven by avoidance of visual predators during daylight or to avoid suboptimal growth conditions. These migrations carry carbon to depth, either within the organisms' bodies, to be excreted at depth as faecal pellets or respired over time and released as dissolved CO_2. This "migrant pump" transports approximately the same amount of carbon to depth (~2 Pg C yr^{-1}) as the physical mixing of the ocean (Boyd and others, 2019; Siegel and others, 2023). This behaviourally driven flux of carbon into the deep ocean is extremely important as these migrations are often down to significant depths (>1 km) where the carbon released may be sequestered away from the atmosphere for more than 500 years (Boyd and others, 2019).

Environmental controls, climate change and anthropogenic impacts

While deep remineralization of sinking material is advantageous in terms of sequestering atmospheric CO_2 in the ocean's interior, it robs the sunlit upper ocean of nutrients and leads to widespread nutrient limitation of primary production (Moore and others, 2013). Processes by which nutrients are returned to the surface, often through stochastic or seasonal mixing, are therefore critical to support continued production. Ocean warming, as a consequence of the ocean absorbing 90% of the total energy generated by anthropogenic forcing of the climate system (Cheng and others, 2022), is likely to alter ocean circulation and mixing (Melet and others, 2022; see sect. 4, chap. 3). While the specific timing and intensity of the

changes are unclear, it is likely to result in changes to the physical replenishment of essential nutrients required for primary production, growth and ecosystem health (Hutchins and Tagliabue, 2024). Current IPCC-class global models vary considerably in their spatial projections of future changes in primary production. Although most exhibit only a modest reduction (~2%) in global marine productivity, there may be strong (>20%) increases (e.g. Arctic) and decreases (e.g. subpolar Atlantic) (Tagliabue and others, 2021) in specific regions.

Another concern is that reduced ocean mixing will reduce the replenishment of oxygen to deep waters (see sect. 4, chap. 3), essential for heterotrophic activity and higher trophic levels. The respiration of sinking organic matter requires oxygen, so there is a net oxygen consumption (deoxygenation) below the sunlit upper ocean. In shallow areas, or where there is sluggish circulation and high rates of sinking organic material and oxygen consumption, this deoxygenation can lead to hypoxic or anoxic conditions (e.g. Meier and others, 2018), the formation of oxygen minimum zones and avoidance of these areas by aerobic organisms (Schmidtko and others, 2017). Reductions in ocean mixing due to ocean warming are predicted to lead to the expansion of oxygen minimum zones and the lowering of oxygen concentrations more generally (Schmidtko and others, 2017) (see sect. 4, chap. 3), which will have a direct impact on ocean biology; for example, limiting the vertical migration of zooplankton (Abedi and others, 2022) and the strength of the migrant pump component of the biological carbon pump (Cavan and others, 2017). Reductions in oxygen availability in the ocean interior may also reduce respiration and remineralization rates, acting as feedback to the biological carbon pump through deeper depth penetration of sinking material (i.e. higher C sequestration) (Cavan and others, 2017).

The ocean's increased uptake of atmospheric CO_2, relative to pre-industrial times, is primarily driven by increasing atmospheric CO_2 concentrations (Sabine, 2021), with the ocean's role in sequestrating anthropogenic CO_2 resulting in chemical changes in the ocean (Sabine, 2021). Specifically, the dissolution of CO_2 and its reaction with seawater to form carbonic acid has dramatically decreased ocean pH (by increasing proton concentrations) and reduced the saturation state of carbonate minerals (calcite, aragonite) in the ocean over the past few decades (Lauvset and others, 2015; Jiang and others, 2019). This "ocean acidification" impacts ocean biology by making the balancing of cell pH (avoiding acidosis) more challenging for marine organisms and increasing the physiological costs of countering the increased dissolution rates of organism-associated biominerals. Ocean acidification impacts the role of marine ecosystems in the carbon cycle at multiple scales (Doney and others, 2020), for example changes in nutrient availability (e.g. Shi and others, 2010), growth, grazing and reproductive success (e.g. Keil and others, 2021), calcification, plankton diversity and community composition (e.g. Taucher and others, 2017). Despite considerable knowledge of ocean acidification impacts on specific elements of marine ecosystems and the biological carbon pump (e.g. Taucher and others, 2017), a holistic understanding of its impact on the future magnitude and efficiency of the different component pumps (gravitational, migrant, mixing) is lacking (Passow and Carlson, 2012; Wolf-Gladrow and Rost, 2014).

3. Shelf, coasts, fjords and estuaries

Moving in from the open ocean, into the shallower areas around coasts, the surface waters continue to fix and cycle carbon through many of the biological processes described in the previous part of the chapter. However, unlike open-ocean environments, coastal areas are more complex and varied, often made up of different, interconnected coastal habitats (such as estuaries (see sect. 4, subchap. 5F), mudflats (see sect. 4, subchap. 5B), salt marshes (see sect. 4, subchap. 5I), seagrass meadows (see sect. 4, subchap. 5G), lagoons and mangroves (see sect. 4, subchap. 5H)), linking the terrestrial zone to the marine through rivers which meet the ocean through deltas, estuaries or fjords (see sect. 4, subchap. 5R). This riverine connection transports organic and inorganic carbon, along with fine particles, into the coastal region, depositing carbon and fine sediment particles (mud) in the nearshore environment (Bianchi and others, 2024). The input of terrestrial carbon into the marine environment is reflected in the carbon sequestered in coastal habitats, which is often a mix of terrestrial and marine carbon, with the proportion of terrestrial carbon higher closer to the coast and marine carbon dominating with greater distance from land (Wilson and others, 2018).

In addition, in coastal zones where sufficient light can reach the sea floor, the seabed plays an additional role in carbon fixation (Legge and others, 2020; Gattuso and others, 2006). Coastal primary production is driven by photosynthesis in plants (see sect. 4, subchap. 4H),

macroalgae (sect. 4, subchap. 4I) or small single-celled photosynthetic organisms (microphytobenthos), which inhabit the surface of soft sediment habitats, such as intertidal mudflats (Christianen and others, 2017). Microphytobenthos dominate carbon cycling in unvegetated coastal sediments (Underwood and others, 2022), play a role in pollutant remediation and form the basis of food webs (Hope and others, 2019). However, the complexity of coastal systems means that, currently, considerable uncertainties remain with regard to estimating the actual area covered by these vegetated coastal habitats, along with considerable variability in specific carbon flux estimates, resulting in a tenfold bracket around the estimates of their contribution to organic carbon sequestration, from 0.073 to 0.866 Pg C yr^{-1} (Duarte, 2017).

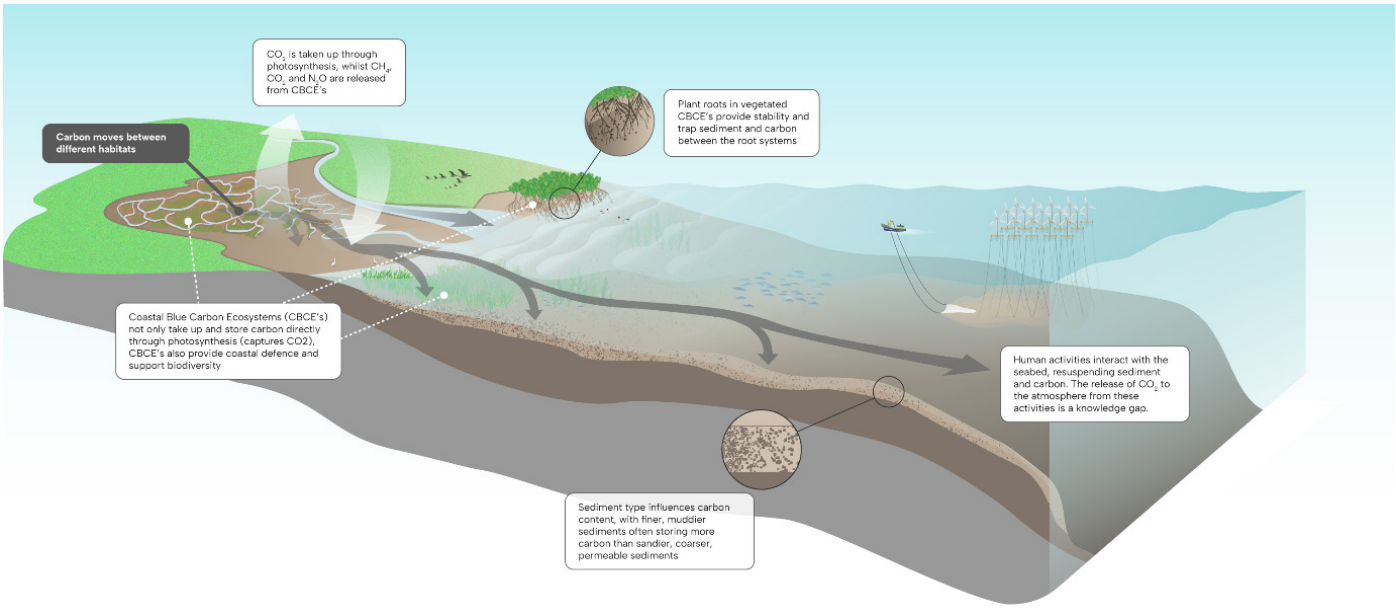
Coastal blue carbon ecosystems

Vegetated coastal habitats such as salt marshes (see sect. 4, subchap. 5I), seagrass meadows (see sect. 4, subchap. 5G) and mangroves (see sect. 4, subchap. 5H), were first described as "blue carbon" habitats in 2009 (Nellemann and others, 2009), and the term is now more generally used for biologically driven carbon fluxes and storage in marine systems that are amenable to management (IPCC, 2021; Lovelock and Duarte, 2019). It is estimated that these three coastal blue carbon ecosystems capture and store more carbon per unit area than terrestrial forests (Mcleod and others, 2011), meaning that, despite covering an area of less than 7 million km^2 (Duarte 2017), coastal blue carbon ecosystems are considered globally important areas of carbon capture and storage. The plants in these ecosystems capture CO_2 directly through photosynthesis (see figure II), and much of the carbon remains within that ecosystem, buried in the soft sediments and root systems around the plants (Macreadie and others, 2014; Saderne and others, 2019). The sediments in these plant-rich ecosystems are key for long-term carbon accumulation and storage, and this permanence (long-term storage of carbon) provides the blue carbon benefit and the potential for climate mitigation (Williamson and Gattuso, 2022). However, not all the carbon stored in coastal blue carbon ecosystems is derived from that habitat (autochthonous), and allochthonous carbon (produced outside of that habitat, e.g. terrestrial origin) can make up a significant portion of carbon stocks in sediments (Cragg and others, 2020; Kharbush and others, 2020). This can have implications for blue carbon accounting (see sect. 4). In addition, a substantial contribution to the carbon sequestration potential of coastal blue carbon ecosystems can come from the export of alkalinity that is produced by anaerobic processes (especially denitrification and sulfate reduction) in sediments and exported laterally through physical water movement (Santos and others, 2021).

The original definition of blue carbon has expanded in recent years as scientific knowledge around carbon uptake and storage in marine ecosystems has increased. Unvegetated marine sediments (coastal, shelf and offshore) store significant amounts of carbon owing to their geographical extent (Legge and others, 2020), despite low accumulation rates compared with coastal zones. The term blue carbon has broadened beyond the original coastal blue carbon ecosystems to include marine sediments (including coastal sediments such as mudflats (Brown and others, 2021) and continental shelf and offshore sediments (Graves and others, 2022)), which store carbon for climate-relevant (at least 100 years) and geological time periods (>1,000 years) but do not directly capture it like vegetated soft sediment habitats (European Marine Board, 2023). Shelf sediments (see sect. 4, subchap. 5B) make up ~9% of the total marine area (Diesing and others, 2017) but hold the biggest carbon store in shelf systems (Legge and others, 2020) and more than 80% of organic carbon is buried in subtidal sediments (Hedges and Keil, 1995; Diesing and others, 2021). The amount of carbon stored in shelf sediments varies with sediment type, and although finer particles and muddier sediments are associated with higher organic carbon content (Bianchi and others, 2024; Legge and others, 2020; Diesing and others, 2017), most of the continental shelf is covered by permeable, sandy sediment, or a mix of mud and sand (Diesing and others, 2021). Sandy sediments hold less organic carbon but a large amount of inorganic carbon, which is generally not considered as part of blue carbon.

As shown in figure II, carbon is directly captured by plants (as CO_2) through photosynthesis in coastal blue carbon ecosystems, while methane (CH_4), nitrous oxide (N_2O) and CO_2 are released by coastal blue carbon ecosystems. Carbon may become stored in coastal blue carbon ecosystems, particularly in the sediment around the root systems, or may flow between the different but connected coastal ecosystems and out onto the shelf (as indicated by the arrow). The largest carbon stores are in the sediments, and carbon stocks vary with sediment type. Human activities (such as fisheries activity or energy infrastructure) that interact with the seabed resuspend sediment and carbon.

Figure II
Major carbon pathways and stores in coastal marine ecosystems



Source: Prepared by the writing team.

Macroalgae and calcifiers

Other organisms play a major role in the coastal biological carbon cycle, such as macroalgae (see sect. 4, subchap. 4I) and calcifying organisms. Macroalgae (such as kelp and seaweed) take up CO_2 through photosynthesis and release it at the end of a growing season when much of the algal biomass dies. Since this vegetation is not rooted in sediment, much of this biomass goes through degradation and remineralization (microbial breakdown into CO_2). Up to 40% may be released into the coastal and open ocean (Krause-Jensen and Duarte, 2016), and a small proportion may be buried in marine sediments (Queirós and others, 2023). Calcifying organisms, such as corals (see sect. 4, subchaps. 5D and 5E) and bivalves (e.g. mussels or oysters), produce solid calcium carbonate in the form of skeletons and shells. While it may seem counter-intuitive, the process of calcification actually emits CO_2 (Pernet and others, 2025), and many calcifiers additionally produce CO_2 through respiration. However, calcifying organisms do play a vital role in the biological carbon cycle, even though they are not considered to be blue carbon, or a nature-based solution for climate change. They are also important for many other species and provide a number of co-benefits, such as habitat provision, supporting biodiversity and improved water quality (see sect. 4, subchaps. 5D and 5E). Recently, coralline algal beds found in sediments have also been suggested to be blue carbon habitats, because the carbon captured and stored through photosynthesis may exceed the carbon released by calcification (James and others, 2024).

Microbial carbon cycling

As in the open ocean, microbial communities make up a significant proportion of the carbon biomass (see part 2 of the present chapter) and drive sedimentary carbon dynamics on the seabed (balance between sequestered and respired). Organic carbon reaches the seabed and is either remineralized through microbial breakdown or consumption of the carbon, releasing CO_2 and nutrients (Middelburg, 2018) or a small proportion may become buried in the sediment and eventually sequestered. The proportion of carbon buried rather than respired is driven not only by microbial activity, which favours aerobic respiration (Glud, 2008), but also by environmental parameters such as temperature and water depth (Diesing and others, 2017) and presence of macrofauna (Middelburg, 2018). Generally, warmer waters stimulate more microbial activity, and a greater proportion of carbon is converted to CO_2 while less is buried. This has implications for reducing carbon sequestration as ocean temperatures warm. Microbial processing of organic carbon determines the flux of oxygen and carbon dioxide (CO_2) at the sediment-water interface (and the sea surface-air interface) and methane in coastal sediments (LaRowe and others, 2020).

Carbon is microbially mineralized in the surface oxic layers of the sediment, the depth of which varies with sediment type and season (Hicks and others, 2017), as muddy sediments with smaller grain size have a shallower oxic depth and have higher organic carbon content than sandy sediments (Bianchi and others, 2024). Below the oxic layer in sediments, the carbon is less easily broken down by microbial communities owing to the hypoxic or anoxic conditions. However, hypoxic or anoxic microbial breakdown of carbon can lead to the release of other metabolites such as ammonium, hydrogen sulfide or methane, another greenhouse gas (Middelburg and Levin, 2009), although a greater proportion of carbon becomes buried in sediments under low-oxygen conditions. This has implications for warming of coastal and marine ecosystems, leading to an increase in the occurrence, duration and frequency of hypoxia (Diaz and Rosenberg, 2008).

Coastal microbial carbon cycling in coastal blue carbon ecosystems is influenced by the presence of plant roots, which provide a route for oxygen to penetrate the sediment layers beyond the oxic zone (Trevathan-Tackett and others, 2023), and microbial communities differ between the coastal blue carbon ecosystem habitats. The origin of the carbon (allochthonous rather than autochthonous) is also important for microbial processing, as marine microbes are less efficient at breaking down land-derived (allochthonous) carbon than marine-derived (autochthonous) carbon (Cragg and others, 2020; LaRowe and others, 2020).

Knowledge gaps and uncertainties

The protection and creation of coastal blue carbon ecosystems are seen as nature-based solutions for marine climate change mitigation (Pörtner and others, 2023) and may contribute to nationally determined contributions under the Paris Agreement 2015, for climate mitigation (Macreadie and others, 2021). Recent estimates suggest that, with full restoration of coastal blue carbon ecosystems, the total contribution to climate mitigation is approximately 2% globally. In temperate regions, the small geographical area of these ecosystems means that it is unlikely that they will play a significant role in meeting mitigation targets. For small island nations, which have a larger geographical extent of coastal blue carbon ecosystems, their relative contribution may be significantly higher. For example, mangroves are found in more than 100 countries, but more than a fifth of global mangroves are located in Indonesia (Macreadie and others, 2019; Giri and others, 2011). The huge global variability of carbon stocks in the same habitat makes it difficult to accurately assess carbon sequestration and climate change mitigation potential, and studies are often underrepresented in the global South (Wasserman and others, 2023).

Recent research has been focused on different approaches to restoration and conservation of coastal blue carbon ecosystems for climate mitigation, particularly as they are vulnerable to sea-level rise in the next few decades. Restoration efforts could include intentional breaching of sea defences or embankments in northwest Europe (called "managed realignment") (Burden and others, 2013; Mossman and others, 2012). Restoration approaches for coastal blue carbon ecosystems, such as realignment, provide a nature-based solution for increasing carbon capture and storage, as well as providing coastal protection from floods and storm surges. However, the role of greenhouse gases in carbon cycling, particularly in coastal blue carbon ecosystems, is not yet fully understood (Williamson and Gattuso, 2022; European Marine Board, 2023), and the climate benefit of salt marshes (natural and restored) is variable (Mason and others, 2023, 2024; Williamson and others, 2024). Studies have shown that coastal wetlands can be emitters of greenhouse gases such as methane and nitrous oxide (Megonigal, 2004; Mason and others, 2023; Roth and others, 2023), although this may be linked to the health and age of the coastal wetland.

Restoration of coastal blue carbon ecosystems for climate mitigation (ability to store carbon) would lead to co-benefits such as coastal protection, increased biodiversity and improved water quality (Williamson and Gattuso, 2022). This is important to recognize, because the climate benefits of restoration, or rewilding, efforts are not likely to be immediate, and it will take time for climate mitigation objectives to be met through the transition of other habitats into coastal blue carbon ecosystems (Burden and others, 2013; Pétillon and others, 2014; Williamson and others, 2024). Coastal blue carbon ecosystems will also need to be climate resilient, in the face of warming and rising sea levels (Macreadie and others, 2019).

Coastal and shelf soft sediments are a significant repository for carbon, and shelf sediments are often highly productive systems with intensive seabed activity. Despite concerns that these carbon stocks could be remineralized into CO_2 through disturbance of the sedimentary carbon stores (Sala and others, 2021), there is limited empirical evidence on the vulnerability of this carbon to anthropogenic activity (Epstein and others, 2022; Hiddink

and others, 2023). This includes trawling, dredging, installation and removal of energy structures and associated infrastructure and deep-sea mining. The uncertainty around the vulnerability of the carbon, and limited knowledge on carbon accumulation rates and burial, makes it challenging to effectively manage the seabed.

4. Exchange between coastal and open-ocean systems

In previous parts of the chapter, the open ocean and the coastal environment have been considered separately. However, these two systems are tightly coupled when it comes to carbon transport, with continental shelf seas being a source of 0.95 ± 0.25 Pg C yr^{-1} to the open ocean (Regnier and others, 2022). This flux consists chiefly of DIC, DOC and particulate organic carbon (POC) and is mainly driven by physical processes. The net transport of DIC is largely driven by enhanced physico-chemical dissolution of atmospheric CO_2 into shelf waters. Shelf seas also typically have higher concentrations of DOC and POC than the open ocean, because of high biological productivity and inputs of DOC and POC from land. Moreover, movement of nektonic animals to and from shelf seas contributes a carbon flux, although this remains very poorly quantified. Quantifying these carbon fluxes is challenging, in part because of the high spatial and temporal variability of shelf seas.

The purely physico-chemical mechanism of shelf-to-ocean DIC flux is mainly driven by wintertime cooling of shelf waters at temperate and higher latitudes, which lowers the partial pressure of CO_2 (pCO_2) in the water and results in uptake of atmospheric CO_2. This cold, dense shelf water can then flow off the shelf and below the oceanic thermocline, a process called the "continental shelf pump" (Tsunogai and others, 1999; Cossarini and others, 2015). Conversely, in tropical shelf seas the opposite can occur: cooler oceanic water can warm up on the shelf, leading to an increase in shelf sea pCO_2 and promoting CO_2 flux to the atmosphere (Lacroix and others, 2021).

Biological production contributes to the continental shelf pump by converting CO_2 into POC and DOC. However, to become part of the continental shelf pump this POC and DOC must either be transported below the open-ocean thermocline or be transformed into refractory DOC, so that the carbon is not remineralized back into CO_2 and exchanged with the atmosphere over short timescales (Lee and others, 2022; Holt and others, 2009). However, most of the POC and DOC produced in shelf seas is remineralized before it can become part of the continental shelf pump, and net biological production rates are not correlated with the strength of the CO_2 sink when comparing globally across shelf seas (Lacroix and others, 2021). Moreover, there can be seasonal and even inter-annual lags between biological production and physical transport, such that shelf sea carbon budgets are not necessarily balanced over a year (Chaichana and others, 2019; Humphreys and others, 2019). The production of biologically refractory DOC, which can accumulate and be exported off the shelf during episodic flushing events, mass transportation of both DOC and POC from shelf to the deep sea by tectonic triggers such as big earthquakes and tsunamis (Kioka and others, 2019), is therefore important for the continental shelf pump; since this carbon is refractory, it does not matter whether this material is exported above or below the thermocline (Chaichana and others, 2019; Humphreys and others, 2019). Part of the POC and DOC that is transported from shelf seas to the open ocean is terrestrial in origin. The fate of this terrestrial carbon remains poorly quantified, but approximately 50% appears to be transported off shelf seas (Lacroix and others, 2021), including below the permanent thermocline (Medeiros and others, 2016). Turbidity currents are an important vector transferring shelf sea sedimentary POC below the oceanic thermocline (Ren and others, 2024; Gibbs and others, 2020; Talling and others, 2024). A distinct increase in coastal to upper slope temperatures gives rise to unstable conditions in the organic rich sediments found under the oxygen minimum zone. The high rate of organic carbon deposition can introduce slope failures by the dissolution of gas hydrates. These non-tectonic slope failures may be an important starting point for the lateral transportation of organic carbons to the deep ocean in the form of turbidites (Kitazato, 2024).

Some organic matter enters the open ocean above the permanent thermocline. Unless it is in the form of refractory DOC, this carbon is not sequestered from the atmosphere, but it can be recycled and fuel primary production off the shelf, and also contribute to the biological carbon pump in the open ocean (Frischknecht and others, 2018). This contribution is partly directly by POC and DOC originating from the shelf, and partly by POC and DOC produced from recycling of organic matter that originated from the shelf.

Horizontal carbon transport through animals is probably widespread but largely unquantified, unlike the vertical flux from animal migrations (see part 2 of the present chapter). For example, fish contribute 16 ± 13% of downward POC flux out of the euphotic zone, but the horizontal carbon flux from fish migrations is unknown (Saba and others, 2021). Physical transport of zooplankton across the shelf break can be significant (Keister and others, 2009) and is even part of the ontogenetic migrations of some commercially important species such as rock lobsters (Phillips and others, 2006). Horizontal fluxes have been estimated in only a few instances. For example, the spawning migration of the squid *Illex argentinus* on the Patagonian Shelf transfers approximately 0.09 Gg C yr^{-1} (0.09 × 10^{-6} Pg yr^{-1}) to the shelf slope (Arkhipkin, 2013), using biomass-to-carbon conversions from Hoving and others, 2017). This is approximately 0.7% of the Patagonian Shelf's net biological production (Lacroix and others, 2021), although it is partly balanced by on-shelf migration of other squid species. Horizontal carbon transport via nektonic animals is likely to be impacted by fishing practices and potentially by climate-induced changes in seasonal and ontogenetic migration patterns.

5. The value of carbon cycling ecosystems

Ocean natural capital accounting encompasses the systematic measurement and reporting of the status or "health" of ocean natural capital, as well as the contributions these assets make to society and the blue economy. Through monetary quantification, the ocean natural capital accounting enables decision makers to make trade-offs and assess impacts associated with various development scenarios and policies for ocean environmental sustainability and human well-being. Marine and coastal ecosystems form natural capital stocks that provide numerous benefits – such as food, climate regulation and air quality control – collectively known as ecosystem services. The value of coastal blue carbon ecosystems can be understood as the total economic value of conserving, restoring and sustainably managing marine and coastal ecosystems, while the concept of total economic value comprises the use and non-use values (Zarate-Barrera and Maldonado, 2015). The valuation of the ecosystem services provided by marine and coastal ecosystems clearly evidences the links between humans and the oceans, informs policymakers for improved ocean management/planning and advance policies and motivates the investment in ocean conservation.

Recently, a country-level blue carbon wealth assessment showed that coastal blue carbon ecosystems have an average value of $190.67 ± 30 billion. Australia, Indonesia and Cuba were the three countries that contributed the most benefits from blue carbon wealth, and India, China and the United States are the largest beneficiaries (Bertram and others, 2021). Of the different types of coastal blue carbon ecosystems, the most extensively studied are mangroves (see sect. 4, subchap. 5H) and salt marshes (tidal marshes). For instance, all the ecosystem services provided by all mangroves worldwide have been valued at $69.9 billion (Sanford, 2009). Regulation services of various coastal wetlands (sect. 4, subchap. 5I) have an average value of $369.7 and a total economic value of $3,184 ha^{-1} yr^{-1}. Mangroves have an average of $806 ha^{-1} yr^{-1} for provision services, $1,446 ha^{-1} yr^{-1} for regulation services, $113 ha^{-1} yr^{-1} for support services, $1,721 ha^{-1} yr^{-1} for cultural services, and a total economic value of $6,553 ha^{-1} yr^{-1} (Lopez-Rivas and Cardenas, 2024). Seagrass meadows (sect. 4, subchap. 5G) are less studied but have an average $3,226.5 ha^{-1} yr^{-1} for provision and $871.7 ha^{-1} yr^{-1} for regulation (Lopez-Rivas and Cardenas, 2024). A study examined the ecological and economic potential of three key ecosystem services – fishery production, nutrient cycling and carbon removal – provided by six kelp genera (*Ecklonia, Laminaria, Lessonia, Macrocystis, Nereocystis* and *Saccharina*). The results show that the potential value of each genus was between $64,400 and $147,100 ha^{-1} yr^{-1} (Eger and others, 2023). There are still gaps in valuation of blue carbon ecosystems. For example, Arkema and others (2024) found that only a third of papers quantify societal benefits of coastal ecosystems within marine protected areas (MPAs), and these tend to focus mainly on corals and mangrove ecosystems.

The value of carbon cycling ecosystems has been increasingly recognized and many finance initiatives exist i.e. voluntary and compliance carbon markets, public funding, philanthropic and other alternatives, such as payment for ecosystem services, ocean natural capital accounting and blue bonds. Blue carbon activities are one type of climate mitigation solution, which currently receives just 3%

of total climate investment globally.[1] This lack of financial support has been a barrier to bringing blue carbon conservation and restoration activities to scale.[2]

The recognition that marine ecosystems, other than coastal blue carbon ecosystems, also have the power to fix and transport large quantities of carbon has increased interest in using them as marine CO_2 removal measures (see subsect. 5A, chap. 10). It should be noted that great uncertainty remains regarding the efficacy, scalability or financial viability of many of these proposed nature-based marine CO_2 removal approaches. For example, the estimated costs for ocean iron fertilization vary widely, with best-case values of $7 per net ton carbon captured, compared with worst-case values of $1,500 per net ton carbon captured depending on oceanographic factors. Ocean iron fertilization aerial delivery ranges between $21 and $2,033 per net ton carbon captured inclusive of verification costs; up to 30–40% more cost-effective than ship-based ocean iron fertilization (Emerson and others, 2024).

While seaweed aquaculture is not considered as either blue carbon or geoengineering (see subsect. 5A, chap. 10), the additional value of such activities to carbon storage, over and above the commercial value of the seaweed product, has been noted. The levelized unit costs (LCOC) of CO_2eq sequestration (LCOC; $\$tCO_2eq^{-1}$) for kelp aquaculture at baseline were estimated at $\$17{,}048\ tCO_2eq^{-1}$, with only a 39% true sequestration "additionality" rate. However, by process improvement and decarbonization of production supply chains LCOC were reduced to $\$1{,}257\ tCO_2eq^{-1}$ and the additionality rate increased to 91% (Coleman and others, 2022). Froehlich and others (2019) analysed global production data and determined that the cost of producing carbon credits from macroalgae ranged from \$71 to $\$27{,}222\ tCO_2eq^{-1}$.

More generally, the recognition of the value of coastal blue carbon ecosystems in climate action has increased in recent years. However, while a total of 81% (158) of the Parties to the Paris Agreement have included an adaptation component in their nationally determined contributions, only 31% (49) identified ocean ecosystems as a priority sector for adaptation. Of the 21% of Parties that included information on ocean or blue carbon as a priority sector for reducing greenhouse gas emissions, 71% mentioned specific ocean-based mitigation measures (UNFCCC, 2024).

1 See https://verra.org/two-new-biosequestration-working-groups/.
2 See https://verra.org/first-blue-carbon-conservation-methodology-expected-to-scale-up-finance-for-coastal-restoration-conservation-activities/.


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Chapter 2
Ocean and human health

Key points

- The health of the ocean and of the human population are inextricably linked within a highly complex network that is global as well as regional.
- Benefits include seafood, medicines from marine organisms and the well-being opportunities of populations living near the sea.
- Harmful effects arise from exposures to algal toxins, pathogens, combustion-derived and synthetic chemicals, microparticles and nanoparticles (particularly plastics), coupled with climate change, biodiversity loss and ecosystem degradation due to excess nutrients (nitrogen and phosphorus), diffuse waste and contaminant mixtures, as well as natural threats.
- Despite various international agreements, marine biodiversity continues to decline, and several ecosystems, such as the Atlantic cod fishery, the Black Sea fishery, and the northern Benguela upwelling system, have declined.
- Identifying a single causative factor for many adverse health effects is overly simplistic: a holistic interdisciplinary approach to ocean and human Health is required to focus on the integrated impact of pollutants and environmental factors, including temperature, salinity, hypoxia and acidification.

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1. Introduction

For millenniums, humans have lived in close proximity to the sea, and the populations of the global coastal zone (within 100 km from the coast) is currently 38% of the human population (Cosby and others, 2024). This trend reflects the range of benefits coastal living offers, including access to marine resources, opportunities to trade by sea and a sense of well-being that many coastal dwellers derive. However, the trend has already resulted in severe damage to marine ecosystems worldwide as humanity has not interacted sustainably with the oceans; and the more benefits acquired, the greater the damage, in turn threatening future benefits (see figure I; Depledge, 2024; Depledge and others, 2013; Moore and others, 2013, 2014). The Black Sea fishery has not yet experienced a total, irreversible collapse, but the combined impacts of long-term overfishing, recent environmental disasters and persistent unsustainable practices, such as ships' ballast water releases,[1] and the report on *The State of Mediterranean and Black Sea Fisheries*[2] indicate that excessive exploitation has diminished in the region, particularly for key species subject to multilateral management plans. All are recovering, although not necessarily at the previous level.[3] However, 73% of commercial species are still overfished and under fishing pressure, which, while lower than in the past, is still double what is considered sustainable (see Sharma and others (eds.), 2025, for information on specific stocks). Unfortunately, numerous international agreements have failed to prevent the progressive introduction of alien species (Depledge, 2024).

Human health and well-being are intrinsically linked with marine ecosystem integrity, depending on the global ocean for food, oxygen, water and climate regulation (Fleming and others, 2019, 2023, 2024). Human health linkages were first promulgated in the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO-IOC) Health of the Oceans component of the multi-agency Global Ocean Observing System in the 1990s.[4] The second *World Ocean Assessment* highlighted the complex network of interactions with ocean and human health, and figure I shows these linkages in much greater detail. Many of these health-related interactions are beneficial, while others can be detrimental (see figure I, adapted from Fleming and others, 2019, 2023, 2024; Landrigan and others, 2020).

Linkages between human health and well-being (see subsect. 5B, chaps. 3 and 4) and the ocean have been known for a long time. New information and understanding by environmental scientists and epidemiologists reinforce the importance of these linkages (Planetary Health Alliance;[5] United Nations Right to Healthy Environment;[6] the Convention on Biological Diversity, Biodiversity and Health[7]). Linkages include benefits such as seafood as a source of protein and micronutrients: at least 3.3 billion people obtain approximately 20% of their dietary protein from this resource (Fleming and others, 2023). Additional health-related benefits are derived from medicines from marine organisms and opportunities to enhance well-being by living near the sea (Fleming and others, 2024; Maycock and others, 2023).

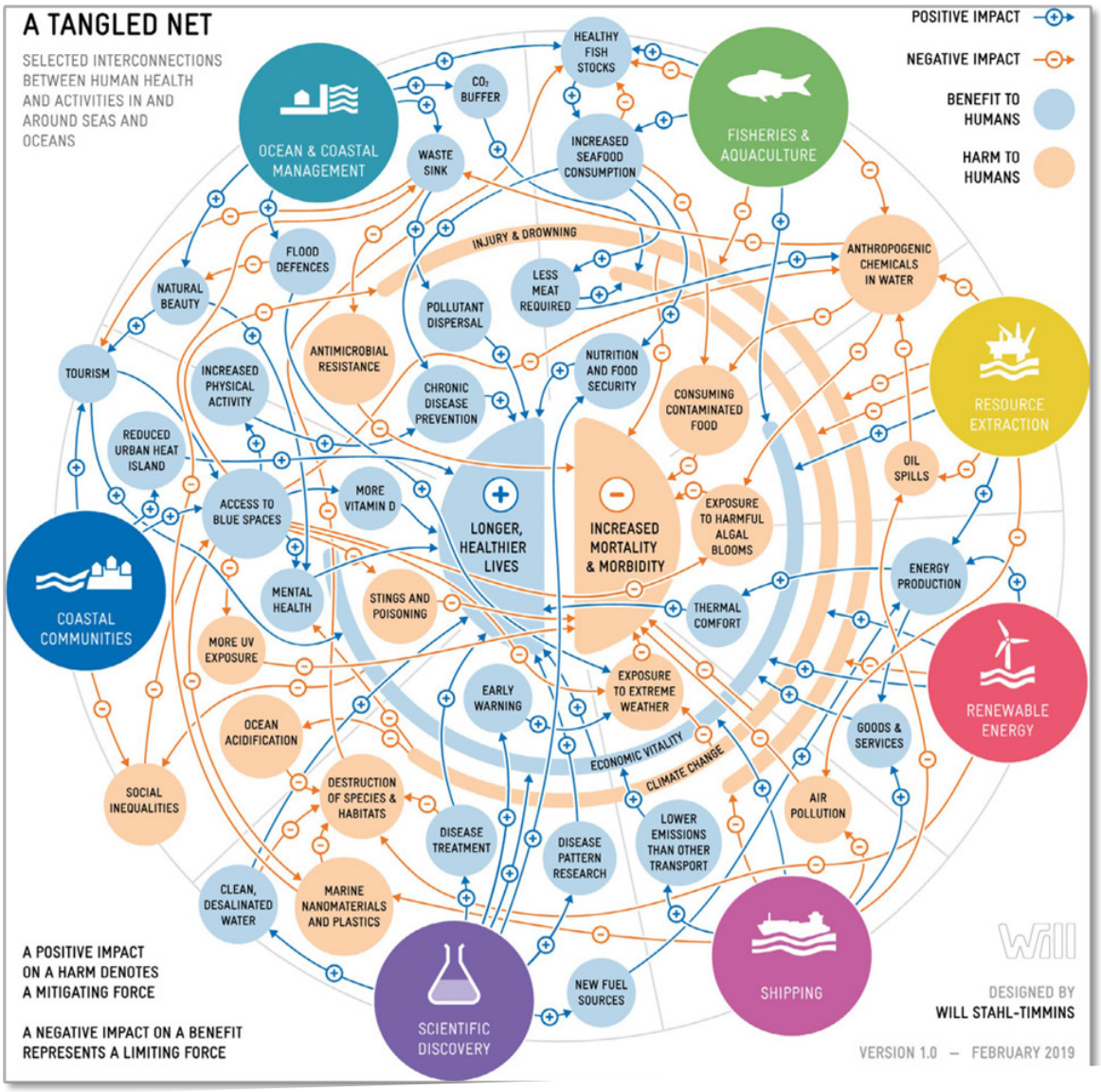
Conversely, negative linkages include adverse impacts on health from exposure to natural and/or anthropogenically sourced events such as exposure to biotoxins from harmful algal blooms (see sect. 4, subchap. 4H); microbial pathogens from sewage and agricultural run-off, agricultural pesticides, offensive odours and pathogens from the presence of animal carcasses/abattoirs, pathogens from hospital waste; chemical/particle pollutants, including nanoplastics and microplastics (see sect. 4, chap. 6); and radiological contamination (see figure II).

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1 See www.europarl.europa.eu/RegData/etudes/BRIE/2025/767238/EPRS_BRI(2025)767238_EN.pdf.
2 Available at https://openknowledge.fao.org/items/53c4dd52-0c42-464d-bdb5-3a4c7c545fb5.
3 See https://openknowledge.fao.org/handle/20.500.14283/cd5538en.
4 See https://unesdoc.unesco.org/ark:/48223/pf0000113893.
5 www.planetaryhealthalliance.org/.
6 See https://press.un.org/en/2022/ga12437.doc.htm.
7 See www.cbd.int/health.

Figure I

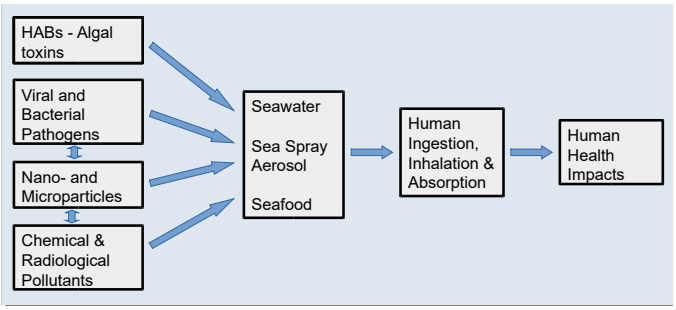
A tangled net: selected interactions between human health and activities in the marine and coastal environment



Source: Adapted from Fleming and others, 2019, with permission from Lora Fleming.

Figure II

Routes of human uptake of harmful biogenic toxins, pathogens, particles and chemicals



Source: Prepared by the writing team.

This chapter contains an assessment of the benefits and adverse impacts from selected ocean-human interactions that are generally global and regional in scope; and emerging health-related issues and problems of future concern are also identified (see tables 1 and 2). Major health challenges discussed below include antimicrobial resistance (AMR), toxic chemical and pharmaceutical contaminants, nanoparticles and microparticles and environmental radiation, all within the context of climate change, biodiversity loss and environmental degradation, such as habitat loss and coastal zone destruction. Socioeconomic decline is associated with marine ecosystem degradation and gives rise to, or exacerbates, pre-existing human physical and mental health issues

(see subsect. 5B, chaps. 1 and 3). Concerns about pollutant mixtures and their potential interactions are also discussed, as harmful contaminants are rarely found in isolation. Lastly, key knowledge and capacity-building gaps are identified, as well as possible actions to effectively monitor and/or measure the risks and benefits of the links between the health of the ocean and that of the human population (see figure I). The ocean's degradation is affecting the enjoyment of human rights, including the rights to health and a clean, healthy and sustainable environment (see the report of the Special Rapporteur on the human right to a clean, healthy and sustainable environment, Astrid Puentes Riaño (A/HRC/58/59).

Table 1

Selected direct and indirect risks, benefits and opportunities for human health and well-being from interactions with the ocean (Fleming and others, in press)

Benefit/ opportunity	Healthy ocean benefit	Potential human health and well-being benefit	Citations
Climate and weather	The ocean is a key player in the regulation of the planet climate; it is critical to the mitigation of climate change.	Prevention of injury, death and mental health impacts from extreme weather.	Villasante and others, 2023; Falkenberg and Joyce, 2023.
Heat and CO_2 sink	The ocean absorbs 25% of all CO_2 emissions and more than 90% of excess atmospheric heat.	Prevention of extreme heat, drought, crop loss, starvation.	Hoegh-Guldberg and others, 2023.
Oxygen	The ocean sustains all life on earth by providing 50% of the oxygen produced on Earth each year and 80% of all the oxygen ever created.	Prevention of crop and other biodiversity loss.	Grégoire and others, 2023.
Biodiversity (including marine protected areas (MPAs))	Biodiversity sustains food webs and ecosystems richness and productivity. Emerging research with communities living in/around MPAs and other areas designated as "protected": diverse human health and well-being benefits; collaborative and effective management with ongoing involvement of local communities essential towards creating and sustaining these ocean and human health benefits.	Livelihoods, improved nutrition. Decreased overall national mortality, and improved child health, as well as positive ecosystem impacts.	Madarcos and others, 2021; Haque and others, 2023; Nowakowski and others, 2023; Ban and others, 2019; Gollan and Barclay, 2020; Rasheed 2020; Winther and others, 2020.
Livelihoods and economics	The ocean is a source of wealth. The ocean economy is estimated to generate $1.5 trillion–$2.5 trillion annually and to provide jobs for more than 30 million people.	Seafood as nutrition and prevention of noncommunicable diseases (NCDs) and mental health impacts.	Dodd and others, 2020; Ocean Panel, 2020.
Marine biotechnology (including marine drugs)	Ca. 30,000 unique molecules, 10% currently known natural products discovered in marine life; 23 approved pharmaceutical agents have been developed from marine molecules, and an additional 33 are in clinical trials. The ocean is a source of new medicines and biotechnologies, from essential pain medicines to plastic alternatives to essential DNA libraries.	Development of treatments for inflammation, immune system disorders, skin pathologies, infectious diseases, NCDs and cancers. Alternatives to plastics and creation of sustainable other biomaterials.	Antunes and others, 2023; CHEMnetBASE, 2023; Pascual-Alonso and others, 2024; Bouley and others, 2023.
Seafood and food security	For more than 3 billion people, nearly 40% of the world's population, the ocean is an essential source of food and livelihood.	Prevention of starvation, childhood stunting, and noncommunicable diseases.	Golden and others, 2021; FAO, Duke University and WorldFish, 2022; Tigchelaar and others, 2022; Golden and others, 2016.
Blue spaces (including culture)	Interactions with the ocean and with other blue spaces enhance the physical health and mental well-being of humans from infancy to old age.	Supports culture, physical health and mental well-being.	White and others, 2021; Fleming and others, 2019.

Threat	Unhealthy ocean risks	Potential human health and well-being risks	Citations
Heat	The ocean absorbs more heat, sea-surface temperature rises: changes in global and local ocean circulation patterns causing increased frequency of extreme weather, polar ice melting, sea-level rise and coastal flooding; migration of fish stocks from dependent communities; increased harmful algal blooms; and pathogen spread.	Death Injury Infectious diseases Starvation Harmful algal bloom illnesses Mental health	Nash and others, 2017; Falkenberg and others, 2021.
Acid	Increased atmospheric CO_2 absorbed by ocean, resulting in low pH causing weakness of calcium skeletons in coral, shellfish and calcium-containing microorganisms sustaining entire marine web; impacts on fisheries.	Starvation Obesity Mental health NCDs Disrupt cultural integrity	Nash and others, 2017; Falkenberg and others, 2020.
Deoxygenation	Dissolved ocean oxygen decreases as water becomes warmer, creating "oceanic dead zones"; impacts on fisheries.	Starvation Obesity Mental health NCDs Disrupt cultural integrity	Grégoire and others, 2023; Falkenberg and others, 2020.
Overfishing	Destructive industrial fishing practices with rising temperatures and pollution damage on ocean ecosystems, biodiversity and fisheries exhaustion.	Starvation Obesity Mental health NCDs Disrupt cultural integrity Jobs loss in small fishery communities, forcing population migrations	FAO, 2022; Golden, Koehn, and others, 2021; FAO, Duke University and WorldFish, 2022; Tigchelaar and others, 2022; Golden and others, 2016; Maycock and others, 2023.
Oil and gas extraction	Fossil fuel extraction and transport with toxic hydrocarbons release, increasing climate change; oil spills: injury, death of marine organisms; destroy biodiversity; impact fisheries.	Death Injury Mental health Increased NCDs Disrupt cultural integrity	Lelieveld and others, 2019; Nash and others, 2017; Landrigan and others, 2020.
Deep-sea mining	Deep-sea mining damages: seabed and vulnerable habitats, radiation releases, impacts on fisheries, biodiversity threats.	Obesity NCDs Possible cancer risk Starvation Disrupt cultural integrity	Hamley, 2022; Miller and others, 2021; Landrigan and others, 2020.
Pollution	80% arises on land from human activities includes plastics, heavy metals, oil wastes, manufactured chemicals, pesticides, radiation and nutrients (including sewage): damages ecological health; biodiversity; impacts fisheries.	Harmful algal bloom illnesses Neurotoxicity Fetal/developmental toxicity Reproductive toxicity Mental health NCDs Cancer Disrupt cultural integrity	Landrigan and others, 2020, 2023; Short and others, 2021.
Economics	Profit-driven, ocean-based economic development with inequitable and short-term economic gain; no concern for protecting and preserving ocean health or for health and well-being of marginalized coastal communities: biodiversity loss and marine ecosystems degradation.	Occupational injury and death Starvation Mental health Disrupt cultural integrity	Germond-Duret, 2022; Das, 2023.

Table 2
Selected adverse human health impacts from ocean interactions

Health threat/ source of toxin/pollutant	Primary exposure route	Known adverse health effects (with key references)	Potential prevention/mediation actions and/or information to support policymaking
Effects of exposure to contaminated seawater, marine aerosols and seafood			
Harmful algal blooms, respiratory distress and toxicity			
Brevetoxins from *Karenia brevis* blooms	Sea breezes during the planktonic *Karenia brevis* blooms	Respiratory distress, asthma exacerbations: Fleming, 2011 (www.sciencedirect.com/science/article/abs/pii/S1568988310000934)	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from sea breezes. Monitoring benthic substrates (mainly macroalgae) on shallow beaches to establish early warnings. Coordination of scientists and local authorities. Increasing awareness of the symptoms among general public and medical professionals.
Non-identified aerosolized toxins (emerging threat), spreading in temperate coasts with global change	Sea breeze during the benthic *Ostreopsis* spp. blooms	Respiratory distress, general malaise: Berdalet and others, 2022 (https://doi.org/10.1016/j.hal.2022.102320) Lemée and others, 2023 (https://anses.hal.science/anses-04169914) Funari and others, 2015 (https://doi.org/10.1016/j.hal.2015.10.008)	
Ciguatera poisoning, endemic in the tropical latitudes, spreading with global change	Ingestion of fish and some molluscs	Complex array of neurologic, gastrointestinal, cardiovascular, respiratory and psychological symptoms: Chinain and others, 2021 (https://doi.org/10.1016/j.hal.2020.101873) Friedman and others, 2017 (https://doi.org/10.3390/md15030072)	Early warning systems for alerting local populations, such as the one implemented in French Polynesia. It includes: • Awareness campaigns to warn individuals against specific risk-taking behaviours (most notably with regard to the fish species and parts of the fish preferentially consumed); • Systematic report of ciguatera poisoning; • Prevention messages provided all year round; • Public meetings conducted alongside field campaigns; • Dissemination tools in local languages for the general public, schools and healthcare professionals. Monitoring benthic species using artificial substrates and quantitative polymerase chain reaction (qPCR).
Paralytic shellfish poisoning (PSP) affecting diverse communities on the Pacific coast of America and in Asia (e.g. the Philippines)	Ingestion of shellfish (e.g. butter clams in Alaska) from subsistence harvesting.	Symptoms include nausea, vomiting, diarrhoea, numbness and tingling of the lips, mouth, face and neck; severe cases: paralysis of chest and abdomen muscles possibly leading to death: Berdalet and others, 2023, in Fleming and others, 2023 (ISBN: 978-0-323-95227-9)	Monitoring toxic species in the water and paralytic toxin in shellfish guarantees food safety; the challenge is monitoring in remote Indigenous communities. This results in economic losses and difficulties for the local inhabitants. The problem affects poorer regions of the planet, especially in Asia and Latin America. No data from Africa.
Extreme Harmful algal bloom (HAB) events, e.g. *Pseudo-nitzschia* blooms in response to the 2014–2016 North-East Pacific marine heatwave, and HABs in Chile.	Massive fish kills, poisoning of marine fauna. To date, no known effects of humans because of strict monitoring, but fauna affectation.	Limited evidence of human poisoning due to *Alexandrium catenella*: Trainer and others, 2020 (https://doi.org/10.1016/j.hal.2019.03.009)	Monitoring of events with reporting of human cases. Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption.

Health threat/ source of toxin/pollutant	Primary exposure route	Known adverse health effects (with key references)	Potential prevention/mediation actions and/or information to support policymaking
Dinophysis (diarrhoetic) in Europe	Ingestion of shellfish	Nausea, vomiting, severe diarrhoea, abdominal cramps, respiratory distress: Reguera and others, 2024 (https://doi.org/10.3389/frpro.2023.1328026)	Monitoring of events with reporting of human cases. Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption.
Allergies, food sensitivities and poisonings from consumption of seafood			
Allergic reactions to seafood	Typically, crustaceans but may include molluscs.	Symptoms include hives, wheezing, trouble breathing, cramps, nausea, vomiting and anaphylaxis: Wai and others, 2020 (https://doi.org/10.3390%2Fijms21062234) Ruethers and others, 2018 (https://doi.org/10.1016/j.molimm.2018.04.008) American Academy of Allergy, Asthma and Immunology, 2024, "Histamine toxicity (scombroid poisoning): overview",[8] updated 2024, accessed 7 July 2024.	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption. Rapid methods to determine toxin concentrations in suspected seafood and clinical specimens. Global database for reporting human and animal allergies, food sensitivities and poisonings from consuming seafood. [One Health Harmful Algal Bloom System (OHHABS) | Harmful Algal Blooms | CDC;[9] National Outbreak Reporting System (NORS) | CDC[10]]. Required reporting for specific foodborne and waterborne diseases [National Notifiable Diseases Surveillance System | CDC[11]] Enhanced seafood monitoring programmes. Modelling to connect environmental data with illness data (e.g. electronic health records [Centers for Medicaid and Medicare Services, www.cms.gov]) to allow prediction of increased risks [Environmental Public Health Tracking Network, https://ephtracking.cdc.gov/].
Food sensitivities and intolerance	Seafood consumption	Symptoms include bloating, flatulence, constipation and stomach pain: Muthukumar and others, 2020 (https://doi.org/10.1016/j.foodres.2020.109780) González-Delgado and others, 2022 (https://doi.org/10.1016/j.jaip.2022.05.006)	
Seafood poisonings	Fresh and processed seafood consumption	Wide range of effects, mostly self-limiting, depending on the toxin involved: Ansdell, 2019 (https://doi.org/10.1016/B978-0-323-54696-6.00049-5) Backer and others, 2004, in Dabrowski and Sikorski, Toxins in Food (https://doi.org/10.1201/9780203502358) Takahashi and others, 2019 (https://doi.org/10.3390/ijms20102435) Landrigan and others, 2020 (https://doi.org/10.5334/aogh.2831)	

8 www.aaaai.org/conditions-treatments/related-conditions/histamine-toxicity.
9 See www.cdc.gov/habs/ohhabs.html.
10 See www.cdc.gov/nors/index.html.
11 See www.cdc.gov/nchs/hus/sources-definitions/nndss.htm.

Table 2 (*continued*)

Health threat/ source of toxin/pollutant	Primary exposure route	Known adverse health effects (with key references)	Potential prevention/mediation actions and/or information to support policymaking
Asthma induction and/or exacerbation	Fish processing activities, skin contact, aerosols	Occupational asthma: Añibarro and others, 2023. Occupational asthma induced by fish exposure - PubMed (nih.gov)	Targeting messaging and enhanced personal protective equipment for those working in fish processing activities.
Microbial infections and parasitic infestations from consumption of seafood and seawater exposure (mainly from human sewage and agricultural run-off)			
Seawater infections		Infections (skin/wound, gastrointestinal, ENT (ear, nose and throat), eye, respiratory, blood) associated with ocean exposure, including plastics: Bowley and others, 2021 (https://doi.org/10.1016/j.tim.2020.06.011)	
Seafood contamination with bacteria	Seafood, ocean plastics exposure	Bacterial infections (skin/wound, gastrointestinal, ENT, eye, respiratory, blood) associated with ocean exposure, including plastics: Iwamoto and others, 2010 (https://doi.org/10.1128/CMR.00059-09) Bowley and others, 2021 (https://doi.org/10.1016/j.tim.2020.06.011)	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption. Global database for reporting human and animal allergies, food sensitivities and poisonings from consuming seafood. [One Health Harmful Algal Bloom System (OHHABS) | Harmful Algal Blooms | CDC;[12] National Outbreak Reporting System (NORS) | CDC[13]]. Required reporting for specific foodborne and waterborne diseases [National Notifiable Diseases Surveillance System | CDC[14]]. Enhanced seafood monitoring programmes.
Vibrio cholera	Seafood	Cholera (severe bacterial gastrointestinal illness): Kanungo and others, 2022 (https://doi.org/10.1016/S0140-6736(22)00330-0)	
Vibrio vulnificus	Seafood	Gastrointestinal disease, gangrene, death: Archer and others, 2023 (https://doi.org/10.1038/s41598-023-28247-2)	
Norwalk virus	Seafood	Gastrointestinal disease: Campos and Lees, 2014 (https://doi.org/10.1128/AEM.04188-13)	
Parasitic illnesses	Seafood	Gastrointestinal disease: Overstreet, 2013 (https://doi.org/10.1007/978-1-4419-0851-3_877)	

12 www.cdc.gov/habs/ohhabs.html.
13 www.cdc.gov/nors/index.html.
14 www.cdc.gov/nchs/hus/sources-definitions/nndss.htm.

Health threat/ source of toxin/pollutant	Primary exposure route	Known adverse health effects (with key references)	Potential prevention/mediation actions and/or information to support policymaking
Antimicrobial resistance (AMR)			
AMR associated with ocean exposure	Water, skin and aerosol exposure, ingestion of seafood, beach sand exposure, ocean plastics exposure.	Resistant or untreatable bacterial infections (skin/wound, gastrointestinal, ENT, eye, respiratory, blood) associated with ocean exposure, including plastics: Sharma and Sumithra, 2023 (https://doi.org/10.1007/978-981-16-9723-4_6-1) Stevenson and others, 2024 (https://doi.org/10.1016/j.scitotenv.2023.168234)	Decreased use of antibiotics, veterinary and human. Increased environmental and human AMR monitoring.
Antifungal resistance (AFR) associated with ocean exposure	Water, skin and aerosol exposure, ingestion of seafood, beach sand exposure, ocean plastics exposure.	Resistant or untreatable fungal infections (skin/wound, ENT, eye, respiratory, blood) associated with ocean exposure: Babič and others, 2022 (https://doi.org/10.3390/jof8080860) Stevenson and others, 2022 (https://doi.org/10.3389/ffunb.2022.918717)	Decreased use of antifungals in veterinary and human medicine. Increased environmental and human antifungal monitoring.
Harmful non-biological pollutants (chemical, particle and radiological pollution)			
General exposure to pollutants			
Chemical exposure to pollutants in seawater, seafood and sediment/sand	Water skin and aerosol exposure, ingestion of seafood, sediment/sand exposure.	Dermatologic, cancer, reproductive, neurologic: Landrigan and others, 2020 (https://doi.org/10.5334/aogh.2831) Multiple toxicological targets: Mezzelani and Regoli, 2022 (https://doi.org/10.1146/annurev-marine-040821-075606) Tacon and others, 2023 (https://doi.org/10.1080/23308249.2023.2238821) Microplastics and nanoplastics can cause alterations of the immune system, inflammation, decreased growth rate and energy unbalance: Nardi and others, 2024 (https://doi.org/10.1016/j.envpol.2024.123327) Radiological injury: Smith and others, 2023 (https://doi.org/10.1126/science.adi5446)	Appropriately targeted messaging for coastal communities regarding ocean-borne risks from seafood consumption. Global database for reporting human and animal allergies, food sensitivities and poisonings from consuming seafood. [National Outbreak Reporting System (NORS) | CDC[15]]. Required reporting for specific foodborne and waterborne diseases [National Notifiable Diseases Surveillance System | CDC[16]]. Enhanced seafood monitoring programmes. Increased research for toxicological pathology related to consumption of contaminated seafood.

15 www.cdc.gov/nors/index.html.
16 www.cdc.gov/nchs/hus/sources-definitions/nndss.htm.

Table 2 (*continued*)

Health threat/ source of toxin/pollutant	Primary exposure route	Known adverse health effects (with key references)	Potential prevention/mediation actions and/or information to support policymaking
Metals			
Industrial and natural processes	Seafood consumption of pollutant metals and metalloids.	Neurotoxicity, oxidative stress and cancers: European Commission, 2023 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32023R0915)	Appropriately targeted testing of seafood.
Petrochemicals, fires and combustion products			
Industrial and natural processes, incomplete combustion, transport and shipping	Ingestion of seafood, inhalation of aerosols and skin contact.	Polycyclic aromatic hydrocarbons (PAHs) are considered toxic primarily due to their carcinogenic potential, meaning they can cause cancer, particularly of the skin, lung and bladder, when exposed to significant levels over long periods; other potential toxic effects include impacts on the reproductive system, immune system dysfunction and developmental issues, especially when exposure occurs during pregnancy; short-term exposure may cause irritation to the eyes, skin and respiratory tract depending on the level of exposure. International Energy Agency, 2018; El-Maradny and others, 2023; Rovira and others, 2021; Hassaan and others, 2024; Landrigan and others, 2020; Liu and others, 2023; Montuori and others, 2021; Shi and others, 2022; Speight, 2019	Appropriately targeted testing of seafood.
Persistent organic pollutants			
Industrial	Seafood consumption.	Oxidative stress, increased cancer risk, reproductive disorders, alteration of the immune system, neurobehavioural impairment, endocrine disruption, genotoxicity and increased birth defects: Ritter and others, 1995; Stockholm Convention (www.pops.int/Home/tabid/2121/Default.aspx)	Appropriately targeted testing of seafood.
Neurotoxic pesticides and agrochemicals			
Agricultural/industrial from wastewater and land run-off	Seafood consumption.	Neurotoxicity contributing to Parkinson's disease and possibly to Alzheimer's disease: Richardson and others, 2019	Appropriately targeted testing of seafood.

Health threat/ source of toxin/pollutant	Primary exposure route	Known adverse health effects (with key references)	Potential prevention/mediation actions and/or information to support policymaking
Pharmaceuticals and endocrine disruptors			
Industrial production, use by the patient or in veterinary use, and ultimate disposal including hospital waste	Bathing and seafood consumption.	Toxicological risks of exposure have not yet been established, although human health assessment for active pharmaceutical ingredients (APIs) contaminating freshwater environments would suggest that the level of risk from this route is likely to be low (WHO, 2012): WHO (2012) Pharmaceuticals in drinking water (www.who.int/publications/i/item/9789241502085) UBA - Umweltbundesamt (2024), Database-pharmaceuticals in the environment (www.umweltbundesamt.de/en/database-pharmaceuticals-in-the-environment-0#undefined) Madikezela and Ncube, 2022	Precautionary approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood and bathing water.
Contaminants of emergent concern			
Industrial waste, domestic wastewater	Seafood consumption.	Endocrine disruption including reproductive and gender abnormalities in marine life and may contribute to human gender dysphoria: Combi and others, 2022; Guo and others, 2023; Cocchetti and others, 2022; Liu and others, 2023; Xie and others, 2022	Precautionary approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood.
Microparticles and nanoparticles (including plastics) and from road run-off			
Industrial waste, atmospheric pollution, run-off from highways and degradation of fibreglass boat hulls	Seafood consumption and inhalation/ ingestion of marine aerosols.	May contribute to endocrine disruption, oxidative stress, dementias and cancers: Amelia and others, 2021; Andrade and others, 2021; Megha and others, 2024; Ciocan and others, 2024	Precautionary approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood.
Environmental radiation			
Nuclear industry and historical weapons testing	Seafood consumption, exposure to bathing water and inhalation/ ingestion of marine aerosols.	Radiation injury, oxidative stress and cancers: Matsumoto and others, 2021; Smith and others, 2023	Appropriately targeted testing of seafood and bathing water.
Pollutant interactions			
Multiple sources: seafood consumption and inhalation/ingestion of marine aerosols	Seafood consumption, exposure to bathing water and inhalation/ ingestion of marine aerosols.	Synergistic and antagonistic toxicities in animal investigations: Forest, 2021; Moore and others, 2021; Albani and others, 2023; Gauthier and others, 2014; Martin, 2023; Moore and others, 2018	Precautionary approach and further toxicological assessment focused on human health. Appropriately targeted testing of seafood.

2. General aspects of the relationship between the ocean and human health

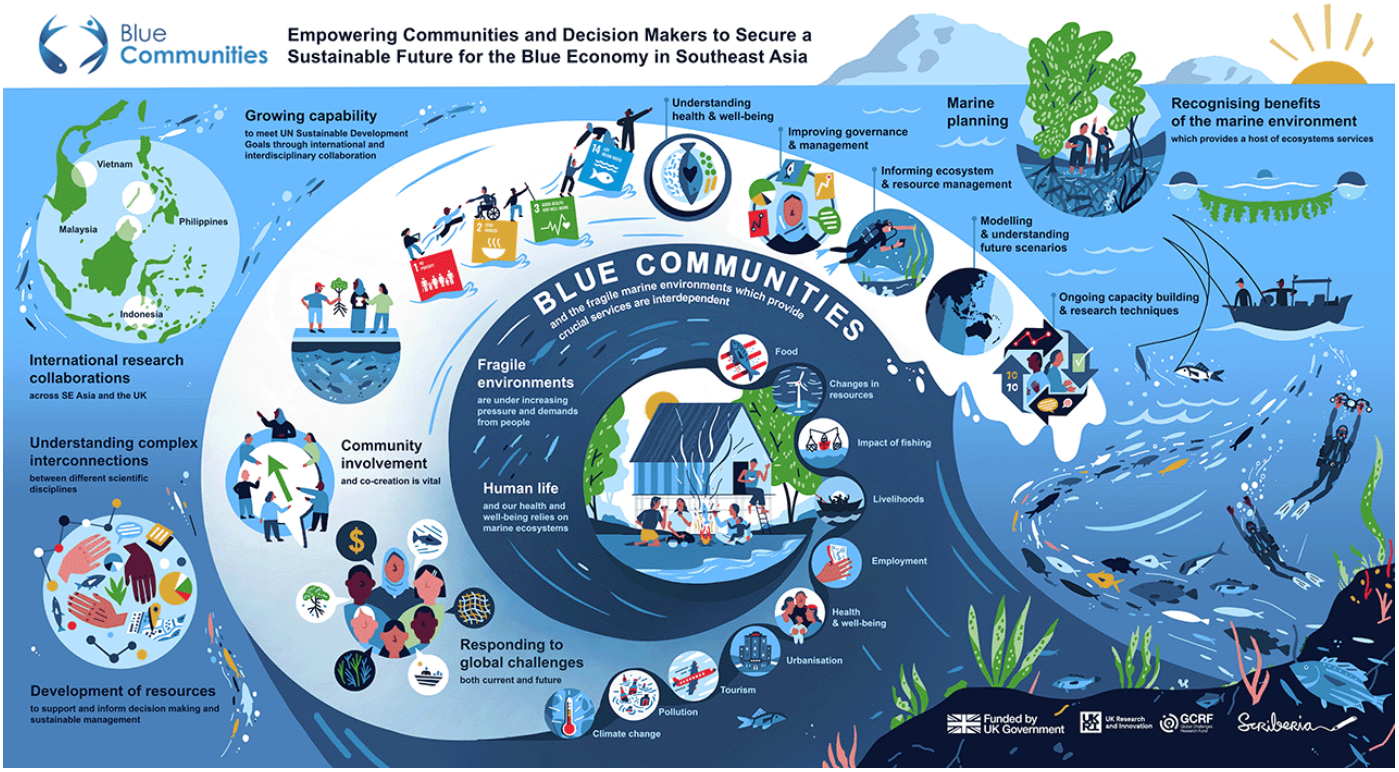
Human health and well-being depend upon the health of the global ocean. The ocean provides food and livelihoods, such as fishing, transport and leisure, for more than 3 billion people (40% of the world's population) and is a source of cultural, spiritual and artistic expression (Fleming and others, 2023, chap. 1, with permission; also figure III).

These interactions can be directly beneficial to human health and well-being in many ways, such as the development of marine-derived pharmaceuticals. Biotechnology and economic benefits can also foster better health and well-being, and there is growing evidence of physical health and mental well-being benefits of blue spaces (see table 1). On the other hand, the ocean can pose severe human health risks because of environmental stressors such as climate change, harmful algal blooms and anthropogenic pollution (see table 1; see also sect. 4, subchaps. 4B, 6A and 6E). These and other changes may diminish ocean biodiversity, and subsequently fisheries and human nutrition, and decrease the potential for discovery and development of marine drugs and beneficial biotechnology (see figure III).

The complex interactions (see figure I and table 1) between the ocean and human health highlight existing challenges and provide insight into emergent and perceived future health challenges, while serving to identify key knowledge and capacity-building gaps. Ultimately, policies and approaches already exist to address many of these ocean-borne challenges to human health and well-being. It is critical to acknowledge the vital importance of a healthy ocean to support human health and well-being now and in the future and to have the will to act sustainably and equitably to protect this relationship.

Figure III

The Global Challenges Research Fund (UKRI – GCRF) Blue Communities Project examined the "health" of the environment and the people living in and around marine protected areas (MPAs) in four South-East Asian Countries



Source: www.plymouth.ac.uk/research/institutes/marine-institute/our-research/blue-communities, with permission from Lora Fleming.

3. Assessment of health benefits (table 1)

Health of coastal communities relative to inland communities

The Global Burden of Disease study[17] found that the relative burden of disease has already shifted from infectious to noncommunicable diseases (NCDs), such as cardiovascular diseases, diabetes and depression, in many countries. It is in the prevention of NCDs that living near the ocean may offer important human health benefits (Fleming and others, 2024).

Relatively poorer coastal communities may benefit most from interactions with the ocean (Garrett and others, 2019), and people living nearer the coast report better overall health (Elliott and others, 2025; Geiger and others, 2023). The benefits of residing near a coast can be seen globally (Maharja and others, 2023) and are enhanced during times of stress, such as the COVID-19 pandemic (Pouso and others, 2021; subsect. 5B, chap. 7). Nevertheless, there are challenges associated with coastal living, as noted in a recent report by the Chief Medical Officer of the United Kingdom (2021),[18] even in a relatively high-income country such as the United Kingdom. Challenges include rapid and human-generated environmental change, social and environmental inequalities, poor investment in infrastructure and a lack of a long-term vision.

Research is beginning to show that communities near marine protected areas (MPAs) and other areas designated as "protected" experience diverse human health and well-being benefits, including decreased overall national mortality and improved child health, as well as positive ecosystem impacts (Madarcos and others, 2021; Haque and others, 2023; Nowakowski and others, 2023). It is clear that collaborative, equitable and effective management of these areas with ongoing involvement and economic improvement of local communities is essential to creating and sustaining these ocean and human health benefits (Ban and others, 2019; Gollan and Barclay, 2020; Rasheed, 2020).

Pharmaceuticals from the sea

Marine-derived pharmaceuticals are currently valued at $4.1 billion and are anticipated to reach $9.1 billion by 2033 (Fact.MR, 2023).[19] As at 2024, there were some 56 marine natural product-inspired pharmaceuticals in use or in human clinical trials (Antunes and others, 2023). For example, one of the fastest-growing classes of anticancer agents, an antibody-drug conjugate, immunologically directs a toxin to selectively kill cancer cells. The toxic component was inspired by dolastatin 10, a natural product of a marine cyanobacterium (Singh and Häder, 2022).

The health of functional marine ecosystems is in danger, and numerous marine species are rapidly disappearing, some of which we do not even get to know (del Monte-Luna and others, 2023). What unique adaptations do these species possess, and how could they benefit human health? This is a loss of unknowable yet presumably vast impact and consequence.

There is an urgent need to characterize, catalogue and use the DNA genetic blueprints of at least representative marine life.

Marine biotechnology

"Biotechnology", broadly defined, encompasses the exploration and application of biological processes for innovation across medicine, agriculture, manufacturing and any other sector that involves living systems. "Marine biotechnology" refers to those innovations derived from, or applied to, the ocean.

For thousands of years, humans have used marine resources for land-based biologic needs (Dias and others, 2012), long before "biotechnology" became an established term. Medicines, foods and food supplements, topical ointments, colours and dyes – each are examples of innovative adaptation of local marine resources and are precursors to the advanced technologies that have emerged over the past century.

17 Available at www.healthdata.org/research-analysis/gbd.
18 Available at https://assets.publishing.service.gov.uk/media/60f98750e90e0703bbd94a41/cmo-annual_report-2021-health-in-coastal-communities-accessible.pdf.
19 Available at www.factmr.com/report/pharmaceuticals-and-medicine-manufacturing-market.

Building on traditional knowledge, anatomists and physiologists have used marine species to achieve greater understanding of basic biomedical processes. Biochemists extracted and isolated compounds for use in modern medicine and cosmetics. Molecular biologists and geneticists developed marine-based laboratory tests, applied enzymes for gene sequencing and are building reference libraries which hold untold biomedical value. Aquaculturists and conservationists are increasingly adopting sophisticated biotechnological techniques to optimize the feeding, reproduction and health of farmed species and wild marine life.

The explosive growth of synthetic biology, artificial intelligence and data science and new genetic tools means that the potential for new biotechnological adaptation of marine resources has never been greater, underscoring the continued importance of protecting and preserving a healthy ocean (Bouley and others, 2023).

Seafood security – sea fisheries and aquaculture

The role that oceans play as a source of healthy food is widely recognized. Foods from the ocean are considered among the healthiest foods, providing a wide range of essential nutrients, some even difficult to find in natural forms in other foods. Seafood provides high-quality proteins, omega-3 fatty acids (n-3 polyunsaturated fatty acids (PUFAs)) and other nutrients, such as iodine and other trace elements and vitamins (Liu and Ralston, 2021; *The Role of Seafood in Child Growth and Development*, National Academies;[20] sect. 4, subchap. 4D; subsect. 5A, subchaps. 1A–1D). The conclusion from the recent *Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption*[21] is very clear. Consumption of aquatic foods is highly beneficial for people at all ages, even when considering potential hazards.[22]

Blue gym and mental and physical well-being

There is growing research evidence that interacting recreationally with unpolluted blue spaces (including the coasts and seas) can have beneficial effects on human physical health and mental well-being, such as antidepression effects (Britton and others, 2020; Depledge and Bird, 2009; Fleming and others, 2024; White and others, 2021).

Coastal residents are more likely than inland dwellers to meet recommended levels of physical activity through recreational exercise (Pasanen and others, 2019), reducing the risk of many NCDs. After correcting for income and other factors, longitudinal studies demonstrate that moving to the coast is associated with sustained improvements in mental health (White and others, 2023). Because of these and other factors, such as generally lower levels of air pollution, several comparative studies across multiple countries indicate that many people living nearer the coast report better overall health and well-being (Elliott and others, 2023; Geiger and others, 2023).

4. Assessment of adverse health impacts (table 2)

Harmful effects of exposure to contaminated seawater, marine aerosols and contaminated seafood

Despite health benefits, many microbial, chemical and particle pollutants and toxins can contaminate seafood. These include marine biotoxins, chemicals produced by certain marine organisms, that cause adverse health effects such as gastrointestinal and neurological symptoms and therefore pose unique food safety concerns (US EPA, "Should I be concerned about eating fish and shellfish?"[23]; Hites and others, 2004; Mol and Coşansu, 2022). According to the World Health Organization (WHO), foodborne illnesses are responsible for approximately 600 million cases and 420,000 deaths each year.[24]

New marine biotoxins and other pollutants are continually being identified, and global demand for seafood continues to grow. Thus, oversight and quality control of seafood should be a priority to prevent future contamination and ensure safe, nutritious and high-quality seafood for consumers (FAO, 2020; subsect. 5A, subchap. 1E).

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20 Available at www.nationalacademies.org/our-work/the-role-of-seafood-in-child-growth-and-development.
21 Available at https://openknowledge.fao.org/items/5430199e-8e5d-43d7-87b0-ee78a4f5658d.
22 See https://openknowledge.fao.org/items/c6a4a48f-3d7a-4df7-b53a-f379cb6cd438.
23 Available at www.epa.gov/choose-fish-and-shellfish-wisely/should-i-be-concerned-about-eating-fish-and-shellfish.
24 See www.who.int/activities/estimating-the-burden-of-foodborne-diseases.

Harmful biological agents (table 2)

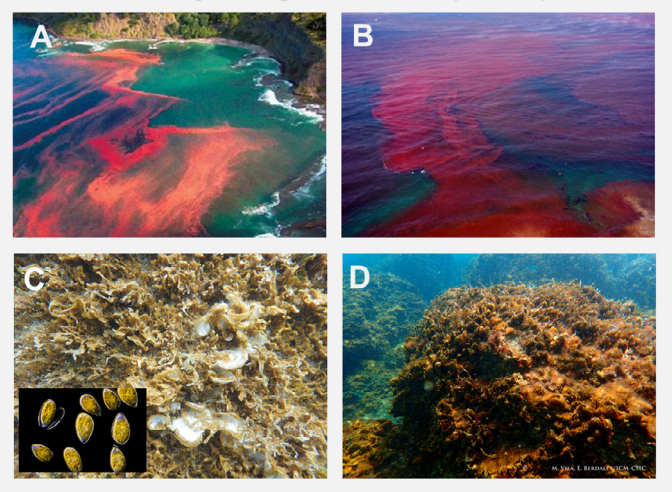
Harmful algal blooms, respiratory distress and toxicity

The term harmful algal blooms refers to a wide range of natural events that occur in aquatic systems that have negative impacts on humans, animals and/or ecosystems (table 2; figure III; GlobalHAB, 2017; Gobler and others, 2017; sect. 4, subchap. 4H and chap. 6; subsect. 5B, chap. 1). Some harmful algal blooms, through their production of natural toxins, cause massive mortalities of wild and cultured animals (GlobalHAB, 2023). Although these toxic compounds can target certain organisms, they can also be transferred through food webs by non-affected vectors and induce adverse health effects in other animals and humans (table 2; Berdalet and others, 2016, 2022; Lefebvre and others, 2016; Zingone and others, 2021).

Major efforts in interdisciplinary research and monitoring of cells and toxic compounds have targeted those harmful algal blooms with demonstrated human health impacts (Hallegraeff and others, 2021). There were 11,000 hospital admissions and 4,000 emergency department visits in 2012 related to harmful algal blooms in Florida (Lim and others, 2023), likely only the "tip of the iceberg" because of misdiagnosis and underreporting. However, in the past 40 years, progress in understanding HAB species-specific dynamics, bloom prediction and effective regulations have been successful in preventing seafood poisonings and mitigating illnesses associated with dermal contact from contaminated water or from inhalation of aerosolized toxins (see sect. 4, subchap. 4H and chap. 6).

Paralytic shellfish toxins (PST) were dominant in East and West Coast America, South America, South-East and North-East Asia; diarrhetic shellfish toxins (DST) in the Mediterranean and Europe; and ciguatera in the Indian Ocean and the tropical Pacific, Australia and New Zealand and Central America and the Caribbean. Currently, adequate monitoring or regulatory tools are in place for DST, PST and amnesic shellfish toxins (AST). However, this is not true for fish-killing harmful algal blooms (Trainer and others, 2020) or for ciguatera toxins for which there are no simple or reliable toxin detection tools (Chinain and others, 2021).

Figure IV
Harmful algal blooms



(A) Red algal bloom at Leigh, near Cape Rodney, New Zealand (*Source*: Miriam Godfrey for the National Institute of Water and Atmospheric Research of New Zealand). (B) Red harmful algae, called *Lingulodinium polyedra*, often produces brightly bioluminescent coloured water discoloration. It has been associated with fish and shellfish mortality events, but its direct threat to human health is still being evaluated (*Source*: Photograph by Kai Schumann, California Department of Public Health volunteer, www.noaa.gov/what-is-harmful-algal-bloom). (C) Images of bloom of *Ostreopsis* cf. *ovata* that causes mortalities among sessile organisms and produces aerosolized toxins (*Source*: Inset: Microphotography of the benthic dinoflagellate *Ostreopsis* cf. *ovata*, by a professional, @ RUBENDURO/SCIENCE INTO IMAGES). (D) Detail of the bloom covering macroalgae, north-west Mediterranean Coast, July 2024 (Source: Photograph by Elisa Berdalet).

Allergies, food sensitivities and poisonings from consumption of seafood

Seafood can be contaminated by naturally occurring or anthropogenic chemicals and toxins, including agents that cause poisonings, allergic reactions and food sensitivities. This part of the chapter (see table 2) focuses on natural toxins, such as saxitoxin and ciguatoxin (Backer and others, 2004) and chemicals that may naturally occur and/or be anthropogenic, such as mercury (Takahashi and Shimohata, 2019). These chemical agents are responsible for both acute poisonings and exacerbation of chronic illnesses. Landrigan and others (2020) published an extensive review of human health and ocean pollutants, including adverse health impacts from exposure to industrial discharges, pharmaceutical wastes, pesticides, persistent organic pollutants (POPs), mercury, and microplastics and nanoplastics.

Allergic reactions may occur after eating seafood, such as shrimp (Ruethers and others, 2018) or fish that has been improperly handled (American Academy of Allergy, Asthma and Immunology, 2024). Food protein-induced enterocolitis syndrome in adulthood can be triggered by consuming seafood, particularly in the presence of other gastrointestinal pathologies such as irritable bowel syndrome symptoms (González-Delgado and others, 2022). These immune-mediated reactions typically occur shortly after consuming seafood.

Seafoods may also induce or exacerbate chronic health conditions. Non-immune-mediated reactions are known as "food sensitivity" or "intolerance" and comprise a delayed response involving the digestive system (Muthukumar and others, 2020; Añibarro and others, 2023).

Microbial infections and parasitic infestations from consumption of seafood and seawater exposure (mainly from human sewage and agricultural run-off)

Marine environments including recreational waters are polluted by human, animal and industrial waste containing diverse microorganisms including viruses, bacteria and single-celled and multicellular parasites. A systematic review of self-reported symptoms of recreational coastal water users in OECD countries indicated that marine recreational water users are approximately twice as likely to report symptoms of illness as non-marine water users (Leonard and others, 2018). The relationship is strengthened in many low- and middle-income countries, where untreated sewage may be discharged to the ocean and elevated temperatures from climate change favour survival and growth of indigenous marine pathogens such as *Vibrio* bacteria (Baker-Austin and others, 2024).

A comprehensive literature review on viruses and bacteria in seafood contained reports of 371,962 cases, 18,723 hospitalizations and 445 deaths associated with 19,554 outbreaks in the United States from 2001 to 2021 recorded by the United States National Outbreak Reporting System (see figure V). More than 450 pathogenic viruses have been detected in sewage and in sewage-contaminated seawater (see figure V; Tisza and others, 2023). Norovirus is an important cause of recreational waterborne gastrointestinal illness (Kennedy and others, 2023) owing to high loads in wastewater combined with a very low infective dose.

Infection risks associated with seafood consumption vary by type of organism and mode of preparation prior to consumption. Bivalve molluscs are of particular concern as they filter large volumes of water and concentrate viral and bacterial pathogens as well as waterborne parasites (Merks and others, 2023). A study of retail mussels in Canada showed between 1.6% and 5.2%, 3.4% and 10.4%, and 0% and 3.3% of packages of fresh mussels and oysters polymerase chain reaction (PCR) positive for *Giardia, Cryptosporidium* and *Toxoplasma*, respectively. Bivalves such as oysters and clams are often consumed raw, increasing the likelihood of pathogen transmission and human infection.

Finfish are the primary source of parasitic worms (see figure VI), and infection is associated with eating raw or undercooked fish (Shamsi and Sheorey, 2018). Larval stages of tapeworms and Anisakid nematodes infect humans from contaminated raw, pickled, smoked or undercooked fish and cause gastrointestinal pathologies and allergic reactions (Audicana and others, 2002).

Antimicrobial resistance

AMR is the ability of microorganisms to withstand drugs used to treat infections. AMR refers to antiviral, antibacterial (or antibiotic) and, specifically, antifungal resistance, and antiparasitic drug resistance. Antibiotic-resistant bacterial infections are a growing pandemic, with 1.27 million deaths directly attributable to antibiotic-resistant infections and 4.95 million deaths associated with these globally in 2019. Antibiotic resistance is often considered to be a clinical phenomenon; however, antibiotic resistance genes frequently acquired by bacteria through horizontal gene transfer are predominantly of environmental origin (Wright, 2007).

Many antibiotic drugs are natural products produced by environmental bacteria and fungi. But less understood is that bacteria have evolved resistance mechanisms in deep evolutionary history, and these are now emerging in human pathogens relevant to global pandemics.

Antibiotic resistance has long been found in soil bacteria. When marine environments were screened for resistance using functional metagenomics, antibiotic resistance genes were found at all sites, with only 28% identified as known resistance genes. There was a high diversity of previously uncharacterized genes, demonstrating the scale of the marine environment as a reservoir of novel resistance genes (Hatosy and Martiny, 2015), with the potential risk of spreading to seafood and humans. For example, bacteria such as *Aeromonas* species are opportunistic human pathogens of aquatic (including marine) origin and are the origin of clinical important resistance genes that have subsequently spread to other human pathogens at a global scale (Ebmeyer and others, 2021).

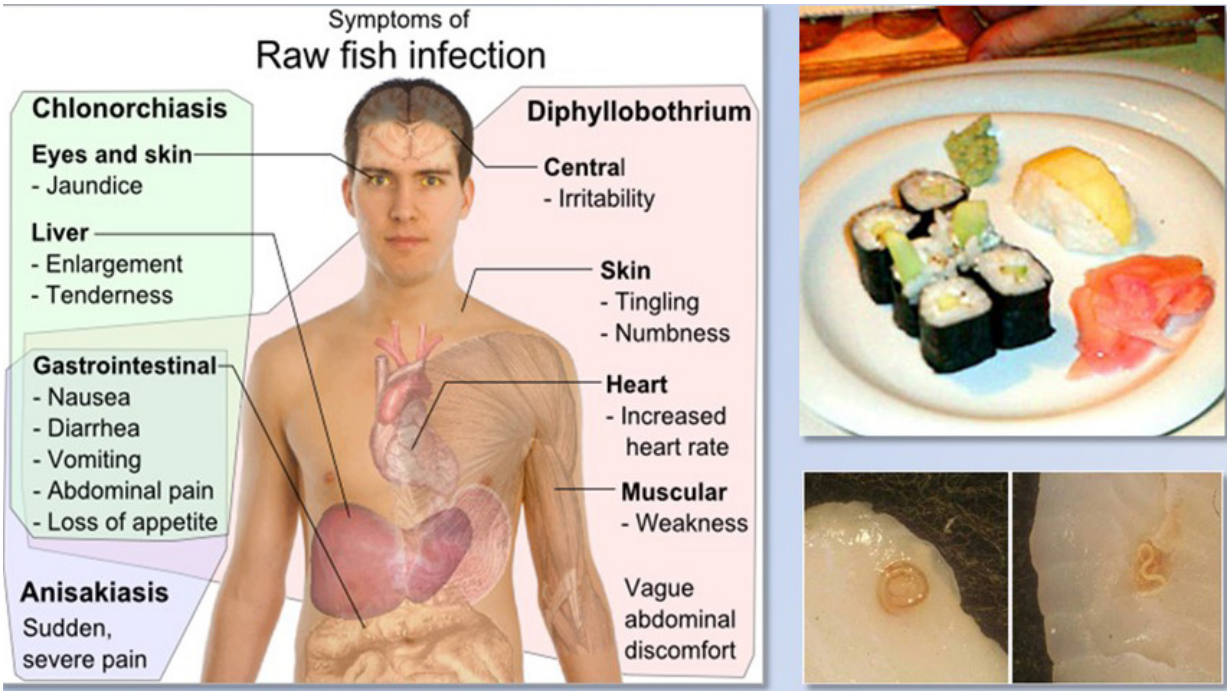
Figure V
Human pathogenic enteric viruses in seawater and seafood

Human enteric viruses with potential waterborne and seafood transmission

Popular name	Diseases caused
Polio	Paralysis, meningitis, fever
Coxsackie A, B	Herpangina, meningitis, fever, respiratory disease, hand-foot-and-mouth disease, myocarditis, heart anomalies, rush, pleurodynia, diabetes? Echo Meningitis, fever, respiratory disease, rush, gastroenteritis
Hepatitis A	Hepatitis
Human rotavirus	Gastroenteritis
Human adenovirus	Gastroenteritis, respiratory disease, conjunctivitis
Norovirus	Gastroenteritis
Sapporo-like virus	Gastroenteritis - to be determined
Hepatitis E	Hepatitis
Human astrovirus	Gastroenteritis
Human parvovirus	Gastroenteritis
Human coronavirus	Gastroenteritis, respiratory disease
Human torovirus	Gastroenteritis

Source: Prepared by the writing team.

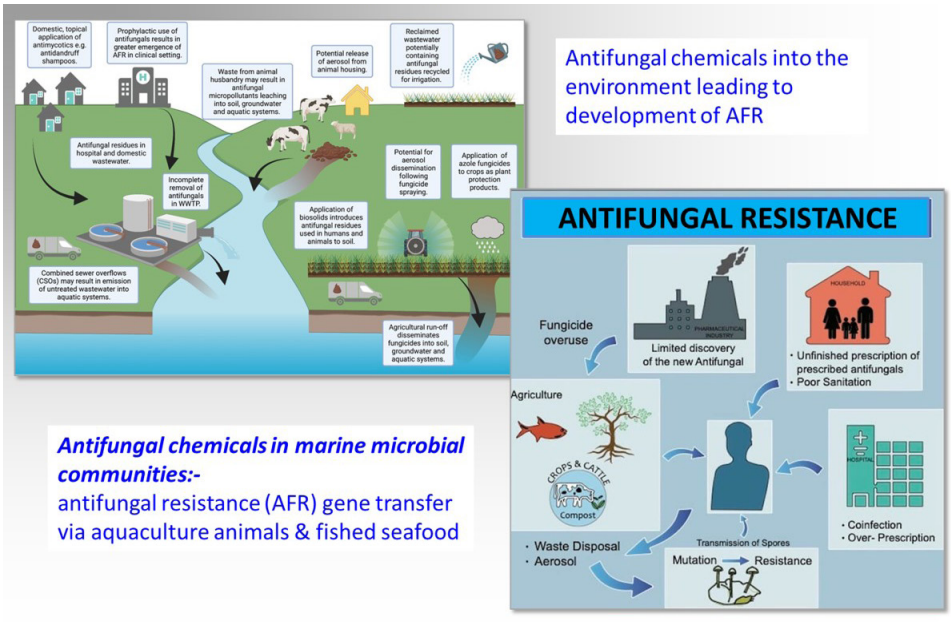
Figure VI
Harmful parasitic worms in seafood, such as sushi and raw or undercooked fish, and symptoms of infection



Source: Adapted from BugBitten – Does your sushi contain parasites?[25]

[25] https://blogs.biomedcentral.com/bugbitten/2017/06/02/does-your-sushi-contain-parasites/.

Figure VII
Pathways for antifungal chemicals entering the marine environment and antifungal resistance



Sources: Adapted from Stevenson and others (2022) and the American Society for Microbiology, Combating antifungal resistance (www.asm.org).[26]

A subset of these bacterial pathogens (and accompanying non-pathogenic commensal bacteria) is resistant to antibiotics. For example, Leonard and others (2015) estimated that 6 million exposure events to a clinically important resistant type of the bacterium occurred (i.e. *Escherichia coli* alone) in United Kingdom bathing waters. Further work illustrated an association between frequent coastal water exposure and gastrointestinal occupation of the same clinically important resistant *E. coli* (Leonard and others, 2018). In addition to being a reservoir of antibiotic resistance and facilitating environmental transmission to humans, the coastal environment may be impacted by pharmaceutical and antibiotic pollution that can select for antibiotic resistance, even at the very low concentrations present.

A recent study of more than 2,000 metagenomic DNA samples sequenced from marine environments revealed that more than 50% of distinct gene clusters were fungal (Cardoso and others, 2020; Laiolo and others, 2024; Ribeiro and others, 2022). In estuarine and coastal environments, antifungal residues from human and animal usage and crop applications may be at sufficient concentrations to select for resistance. However, an understanding of minimal selective concentrations of antifungals required to drive the evolution of resistance is just emerging (see figure VII; Stevenson and others, 2022). There are also health concerns around antifungal-resistant fungal pathogens in wastewater inputs in coastal waters with the presence of *Aspergillus* and *Fusarium* isolates resistant to antifungals (Assress and others, 2020).

Harmful non-biological pollutants (table 2)

Toxicity from chemical, particle and radiological contaminants

Non-biological pollutants in seafood can represent a serious health risk (Tacon and others, 2023). Although industrial production of potentially toxic chemicals is estimated to be more than 350,000 substances,[27] only a minimal number of these have been identified and quantified in the environmental matrices by national environmental agencies. Seafood animals accumulate chemicals from seawater, sediments and/or diet with different outcomes according to tissues and species. Specific classes of chemicals, such as POPs and mercury, represent a higher risk for human consumption (Al-Sulaiti and others, 2022; see specific subparts below).

26 See https://asm.org/articles/2022/november/combatting-antifungal-resistance.
27 See www.cas.org/press-releases/common-chemistry; www.ciel.org/reports/science-denial-toxic-chemical-regulation/.

Environmental pollutants can be classified according to the biological mechanisms leading to chronic rather than acute health conditions (Mezzelani and Regoli, 2022). Exposure over time to endocrine disruptors in seawater, sediments, aerosols and seafood can alter hormonal balance in both animals and people. Other chemicals can interact with several cellular receptors to alter biological pathways, including those of lipid metabolism with obesogenic effects. Carcinogenic substances can damage DNA following their biotransformation or through oxidative mechanisms with increased production of reactive oxygen species.

Particles such as microplastics and nanoplastics have been increasingly reported in all species of marine food webs and in human tissues (Vital and others, 2021; Tan and others, 2023). Toxicological potential of microparticles and nanoparticles is inversely related to size; below 20 µm down to nanoscale, alterations of immune system, inflammation, decreased growth rate and energy imbalance have been reported (Nardi and others, 2024). Radioactive contaminants in seafood might potentially affect human health because of the intrinsic long-term risk potential of radiation to cause mutations and an increased risk of cancer (Smith and others, 2023).

Metals

Many metals and metalloids can impact the health of both aquatic organisms and humans; therefore, maximum permissible concentrations in fish and shellfish exist for mercury (Hg), arsenic (As; metalloid), cadmium (Cd) and lead (Pb) (European Commission, 2023; Raj and Das, 2023).

The main ocean-related toxicity of mercury derives from its bacterial methylation to MeHg, rapidly accumulated and biomagnified, and accounting for up to 100% of total mercury in seafood. MeHg is neurotoxic for the developing nervous system, and dietary guidelines have been provided for a safe level of fish consumption by pregnant women (U.S. EPA and FDA, 2024). Long-term exposure to cadmium (Cd) results in renal dysfunction, osteoporosis and some cancers in humans (Satarug and others, 2017). Humans can be exposed to arsenic through the consumption of fish contaminated with arsenic. However, non-toxic organic species of arsenic are believed to be the dominant form of arsenic in fish and shellfish, although other organic metabolites produced by gut microbes may be more toxic (Chandel and others, 2024).

Petrochemicals and combustion products

Petrochemical and combustion products such as polycyclic aromatic hydrocarbons (PAHs) are ubiquitous substances in the marine environment (Hassaan and others, 2024; Landrigan and others, 2020; Montuori and others, 2021; Speight, 2019). Contamination problems are due to human activities such as petroleum extraction, transport, shipping, chemical transformation and their use (International Energy Agency, 2018; Rovira and others, 2021; UNEP/RAMOGE, 1999; subsect. 5A, subchap. 3B).

Petrochemical and PAH combustion product contamination may be used to evaluate risk for human health from exposure to petrochemicals and combustion processes (Long and others, 1995; Ma and others, 2017; Montuori and others, 2021; Nourian and others, 2024). However, the risk related to these products should be considered as a component of the general evaluation of human health risk due to the mixture of contaminants present in a particular marine environment, along with other factors such as climate change (see information on pollutant interactions below).

Persistent organic pollutants

POPs are hazardous chemicals that threaten human health and ecosystems; for example, polychlorinated biphenyls (Ritter and others, 1995; Stockholm Convention). POPs remain intact for a long time, are widely distributed throughout the environment, bioaccumulate and biomagnify in living organisms through the food chain and are toxic to both humans and wildlife (see sect. 4, chap. 6). Furthermore, as a result of releases to the environment over the past several decades due to human activities, POPs are now widely distributed over large regions. This extensive contamination of both the environment and living organisms includes many foodstuffs, resulting in sustained exposure of many species (including humans) for periods of time that span generations, leading to both acute and chronic health effects.

Neurotoxic pesticides and agrochemicals

Wastewater and land run-off of the most common insecticides, herbicides, fungicides and rodenticides represent a significant environmental and health threat because the same molecular targets attacked in pests are also present in other species, including diverse marine life and humans (Richardson and others, 2019). Neurotoxic effects in humans are supported by their detection in

brains of patients affected by Alzheimer's and Parkinson's diseases (Paul and others, 2024). Acaracides, such as rotenone and pyridaben, can cause human neurological disorders, including the possible pathogenesis of Parkinson's disease.

Pharmaceuticals and endocrine disruptors

More than 2,000 active pharmaceutical ingredients (APIs) are approved for use around the globe. APIs can be released to the environment during their production, patient and veterinary use, and their ultimate disposal.

Monitoring of APIs in the marine environment has been carried out in North America, Asia, Africa, Europe, Latin America and Antarctica (UBA, 2024). Substances detected in seawater and estuarine waters included compounds from analgesic, antibiotic, antidepressant, anti-inflammatory, beta blocker, oestrogen, and lipid-lowering agent classes (UBA, 2024). Concentrations in water are typically in the low ng/L range or below (UBA, 2024; Leonard and others, 2020; see also the information on neurotoxic pesticides and agrochemicals above).

Monitoring of fish and shellfish demonstrates that many of these APIs are taken up by these organisms and potentially enter the food chain; therefore human exposure is possible (Madikezela and Ncube, 2022). Assessments have estimated the toxicological risks of seafood contamination to human health; these indicate that, in some instances, concentrations of APIs are at levels that might cause harm to humans (Fehrenbach and others, 2022).

Consequently, there are increasing health risks from endocrine disruptors by being exposed to concentrated emerging chemicals through the consumption of contaminated seafood (Alvarez-Muñoz and others, 2018; Landrigan and others, 2020).

Contaminants of emergent concern

Emerging contaminants in marine environments, such as detergents, personal care products (PCPs), perfluoroalkyl and polyfluoroalkyl substances (PFAS - "forever chemicals") (see figure VIII), and plastic additives, pose significant threats to marine organisms and human health (Combi and others, 2022; Guo and others, 2023). PCPs (including triclosan, ultraviolet blockers, parabens and oxybenzone) are commonly found in sunscreens, shampoos and lotions (Chakraborty and others, 2023; Pironti and others, 2021; Vuckovic and others, 2022; Xue and others, 2017).

Flame retardants and plastic additives are widespread in the ocean and can cause reproductive and gender abnormalities in marine life owing to their endocrine-disrupting properties (Cocchetti and others, 2022; Liu and others, 2023; Xie and others, 2022).

PFAS are ubiquitous in coastal waters and are bioaccumulated in the human seafood chain (Sonne and others, 2023). Exposure to all pollutants is particularly concerning for Indigenous and other coastal communities with high seafood diets: they face significant health risks, including immune suppression as identified by the European Food Safety Authority (see figure VIII; Bilela and others, 2023; Chen and others, 2023; Ford and Ginley, 2024).

Microparticles and nanoparticles (including plastics) from road run-off

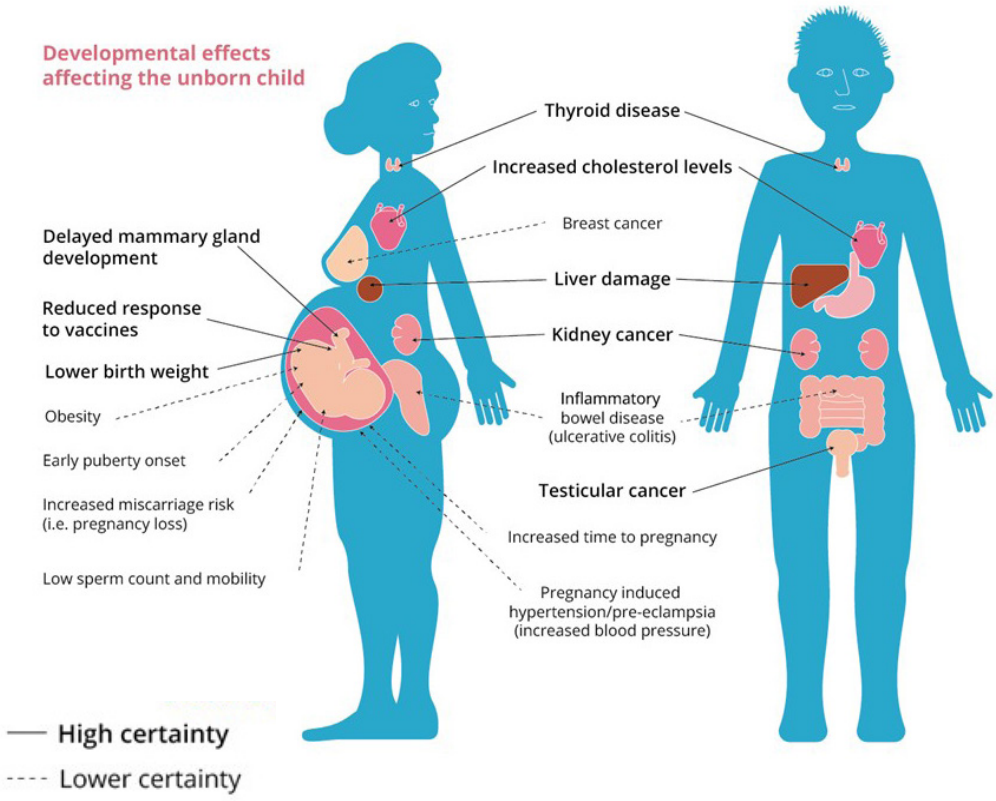
Nanotechnology is generating increasing amounts of nanomaterials that enter the marine environment (Gonçalves and Bebianno, 2021). Other nanomaterials and micromaterials are generated by various combustion and frictional processes; of particular concern are what are known as "hidden plastics" (Mayer and others, 2024). These nanoplastics and microplastics are produced by frictional and partial combustion of vehicle tyres. Tyres are approximately 25% plastic and tyre dust contributes to particulate air pollution and road run-off draining into marine environments and comprises approximately 28% of all nanoplastic and microplastic pollution (see figure IX; Mayer and others, 2024; Obanya and others, 2024; Sieber and others, 2022).

Evidence for harmful human health effects of these particles, as well as other various nanoparticles, is growing rapidly, with ingested and inhaled particles finding their way into most human organ systems, as well as emerging evidence for endocrine-disrupting effects (see figure X; Leso and others, 2023; Wang and others, 2023; Yee and others, 2021). Routes of particle uptake include consumption of seafood and inhalation/ingestion of nanoparticles in marine aerosols (i.e. sea spray) (see figures II and X; Lambert and others, 2024; Luo and others, 2025; Patil and others, 2022; Li and Liu, 2024).

Microplastics and nanoplastics serve as transport vectors for many chemical additives and adsorbed chemicals in the ocean which are persistent, bioaccumulative, mobile and toxic to the marine fish and other organisms (Amelia and others, 2021; Andrade and others, 2021). Consequently, microplastics and nanoplastics,

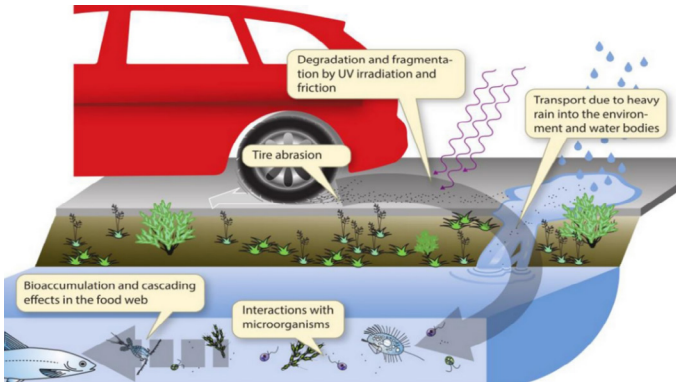
chemical additives and adsorbed chemicals, such as polycyclic aromatic hydrocarbons, can lead to potential adverse health effects in marine organisms and humans (Aatmeeyata, 2010; Megha and others, 2024).

Figure VIII
Effects of perfluoroalkyl and polyfluoroalkyl substances on human health



Source: European Environment Agency, *Emerging Chemical Risks in Europe*: 'PFAS' (2023) (see Effects of PFAS on human health. European Environment Agency's home page, www.eea.europa.eu/en/analysis/maps-and-charts/effects-of-pfas-on-human-health).

Figure IX
Tyres contain approximately 25% plastic, and frictional heating and breakdown into tyre dust from road contact generates toxic and carcinogenic polycyclic aromatic hydrocarbons and nanoplastic particles



Sources: Adapted from Sieber and others, 2022; Aatmeeyata, 2010; Mayer and others, 2024.

A new issue of health concern is the presence of microfibres and nanofibres of glass in edible filter-feeding molluscs from degradation of fibreglass hulls of boats, including derelict boats (Ciocan and others, 2024).

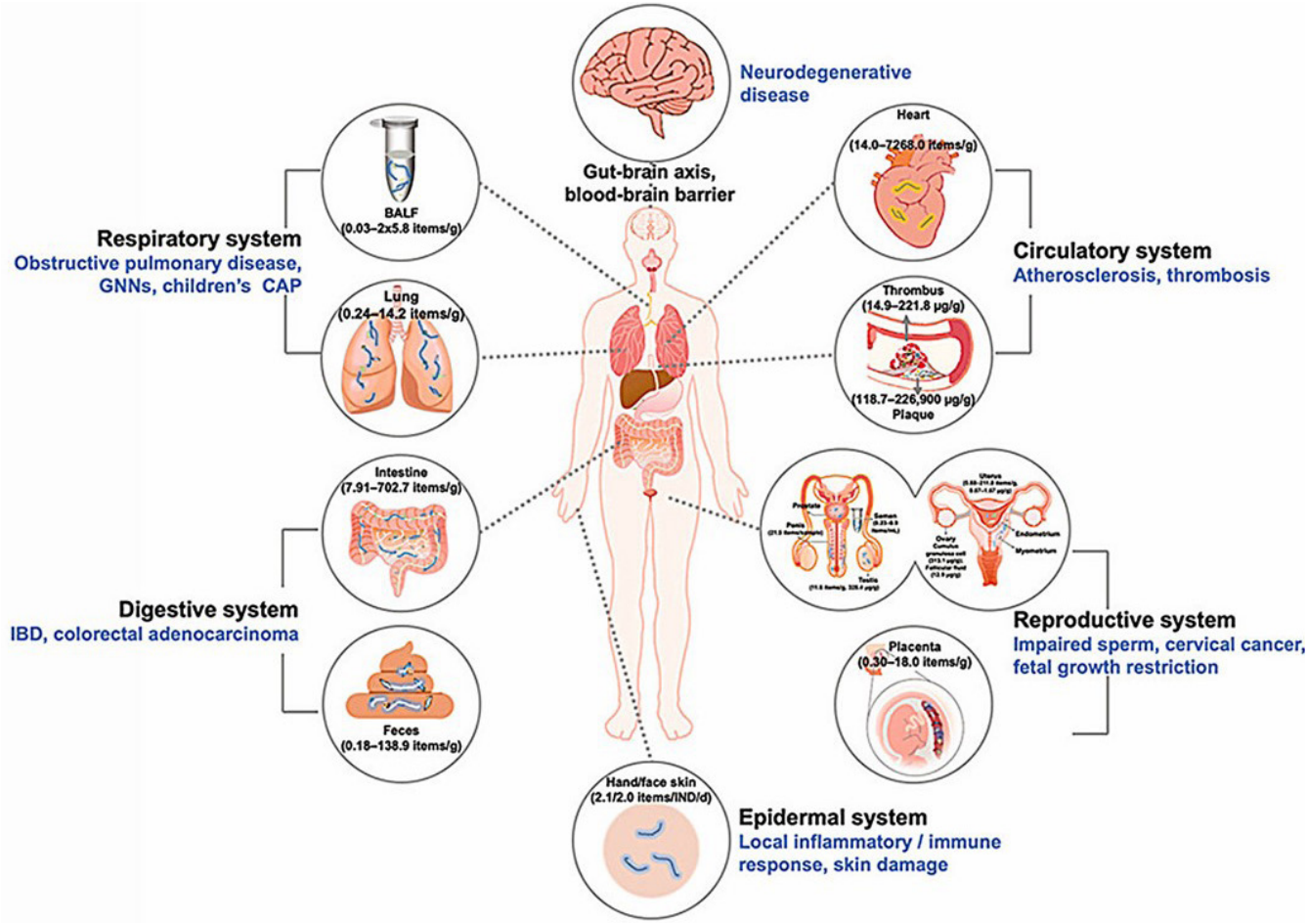
Environmental radiation

Along with other contaminants, the seas and global ocean are the ultimate recipient of anthropogenic radionuclides. For example, 5.9 × 10^{18} becquerel (Bq) of tritium, is discharged in quantities much larger than any other radionuclide (see figure II; Ferreira and others, 2023, 2024; Matsumoto and others, 2021). And 90% of this radionuclide is present in the oceans, compared with 9% and 1% in continental waters and the atmosphere, respectively. In this context, the Pacific Ocean currently contains 500,000 TBq of natural and 2,500,000 TBq of anthropogenic tritium, the latter mostly from past atmospheric nuclear weapon testing (Smith and others, 2023).

The International Atomic Energy Agency (IAEA) concluded in its *Comprehensive Report* of July 2023 that the discharge of ALPS-treated water into the sea from the Fukushima Daiichi Nuclear Power Station is consistent with relevant international safety standards and that the discharge will have a negligible radiological impact on people and the environment (IAEA, 2023). There are, however, many unresolved issues in relation to potential short- and long-term impact related to controlled release of radioactive water following the Fukushima Daiichi nuclear accident (Ferreira and others, 2024). It is therefore necessary to continue to monitor whether the discharge is being managed as originally planned.

According to the United Nations Scientific Committee on the Effects of Atomic Radiation,[28] DNA is the most important target for the action of ionizing radiations. Damage to DNA, if not repaired, is the ultimate cause of many cancers and is associated with many other harmful health impacts. Exposure to radionuclides through different routes, such as consumption of seafood, inhalation or skin penetration, therefore poses health risks (Matsumoto and others, 2021). To protect human health, biokinetic models have been developed for specific radionuclides, within specific organs. Data from biokinetic models are then used to calculate absorbed radiation doses and potential biological effects for each target organ (Paquet and others, 2016). It is emphasized that, in order to minimize the presence of hazardous waste, Sustainable Development Goals 12 and 17 should be redefined to include radioactive waste and promote environmentally sound technologies (Wimmers and von Hirschhausen, 2024; Wimmers and others, 2023).

Figure X
Potential harmful effects of ingested and inhaled microplastics and nanoplastics



Source: Adapted from Patil and others, 2022.

[28] United Nations, report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly at its sixty-first session, with scientific annexes (New York, 2009), available at https://digitallibrary.un.org/record/671062?v=pdf.

Pollutant interactions

It is now well established that biological effects of environmental contaminants are due to their cumulative actions (Bopp and others, 2018; Kienzler and others, 2016). The toxic effects of contaminants present in a mixture may be additive, and even in some cases antagonistic (Forest, 2021; Moore and others, 2021); however, synergistic effects of toxic chemicals are also well demonstrated (Albani and others, 2023; Gauthier and others, 2014; Martin, 2023; Moore and others, 2018). Obviously, there is a clear need to estimate risk for human health from marine pollution, taking into account all available chemical data in terms of contaminant concentrations in waters, sediments, aerosol and seafood. It is important to evaluate the biological effects of contaminants on seafood organisms exposed to all bioavailable contaminants (Dagnino and Viarengo, 2014; Davies and Vethaak, 2012; Viarengo and others, 2007) to gain a more complete overview of toxicity and risk.

5. Key remaining knowledge and capacity-building gaps

There clearly remain many unknowns in the field of human health-marine environmental interactions (see figure I). However, there is considerable evidence for research progress and a better understanding of the many and often interconnected areas of interest to scientists and regulators (see figure XI).

Figure XI
Key remaining knowledge and capacity gaps that are essential to address for effective ocean regulation and management



Source: Adapted from Moore and others, 2014.

Continuing emphasis should be placed on the following key problem areas and issues of emerging concern given the socioeconomic importance of environmental interactions with human health:

1. Current lack of an effective international interdisciplinary panel or forum that includes: environmental epidemiologists; public health, biomedical and environmental scientists; clinicians, environmental psychologists, lawyers and economists; marine ecologists and oceanographers; and environmental regulators and managers.
2. The High Level Panel for a Sustainable Ocean Economy (https://oceanpanel.org) has produced a number of reports on various aspects related to human health but only one specific report.[29]
3. Important to start linking human health and well-being indicators with ocean "health" indicators, and exploring long-term impacts (risks and benefits) of changing ocean health on human health; and recommended in the Ocean Panel ocean and human health (OHH) report (https://oceanpanel.org/publication/ocean-human-health/) as one of three major recommendations.
4. Recognition that actions intended to ameliorate risk from particular factors may have unintended adverse consequences for ecosystems and human health.
5. The evidence indicates that pollution is causing serious health issues, so why are many national authorities not taking action to protect people?
6. Promotion of sustainable and equitable use of decreasing marine resources as a result of increasing population and demand.
7. Recognition of the benefits of increasing interdisciplinary research efforts into oceans and human health.
8. Suggest effective monitoring and quantitative assessment (where possible) of risks and benefits of interlinked human and ocean health.
9. Try to ensure that data are truly available and transparent for use by communities and others.
10. Increase sustainable and equitable efforts to identify potential marine pharmaceuticals and other natural products.

[29] https://oceanpanel.org/publication/ocean-human-health/.

11. Try to ensure that seafood monitoring programmes are effective and up to date for biotoxins, pollutant chemicals and micromaterials and nanomaterials.
12. Suggest increasing efforts to reduce the impact of antimicrobial and antifungal resistance in relation to seafood and aquatic systems.
13. Aim to end microbial, chemical (including pharmaceuticals) and particulate pollution of the oceans.
14. Suggest support for a global ban on the production of single-use plastic and promote effective plastic waste management.
15. Recognize that unpredictable emergent future health challenges will occur.
16. Recognize that climate change will result in the geographical redistribution of human pathogens, and that enhanced storm-related disturbance of coastal sediments, and erosion of nearshore landfill sites, will release chemical pollutants and other types of waste.
17. Recognize the importance of serendipity in scientific discovery, such as the production of "dark" oxygen from seafloor metal-rich nodules (Sweetman and others, 2024); the possible role of algal toxins in inhaled/ingested sea spray aerosols having a beneficial health effect (Van Acker and others, 2021); and the role of environmental endocrine disrupters in gender dysphoria (Cocchetti and others, 2022).
18. Recognize the benefits of developing an integrated modelling capacity for predicting environmental impacts on human health (Allen, 2011; Moore and others, 2014).
19. Suggest extending regional and international marine pollution-control programmes to all countries.

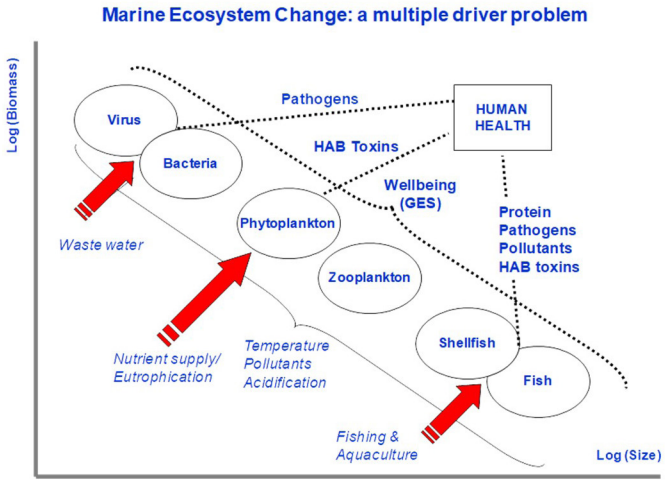
6. Conclusions and vision

The global ocean provides humans with many benefits, including the production of healthy seafood. The marine environment can also be the source of potential health benefits by providing novel pharmaceuticals and related natural products derived from marine organisms, as well as contributing to disease prevention and treatments through encouraging physical activity and enhancing psychological well-being (see table 1).

The complexity of ocean-human interactions is increasing, with mixed exposures from contaminated environments to harmful algal toxins, pathogenic bacteria and viruses, anthropogenic (man-made) chemicals (including microplastics and nanoplastics), as well as other types of pollution. Untangling the relative contributions and interactions of these stressors is challenging, particularly when coupled with climate change, biodiversity loss and ecosystem degradation of the global ocean (see table 2; figures I and XII; Allen, 2011).

It is crucial that all of these stressors be considered in depth globally to understand the complexity of interactions between the ocean and human health (see figures I, II and XII). At its core, there must be a well-thought-out and clearly articulated vision of what would be an acceptable relationship between humans and the oceans in the future. This means accepting and embracing that the current and future state of the global ocean will in large part determine current and future sustainability and the health and well-being of all humans on Earth.

Figure XII
Schematic diagram illustrating the multiple drivers underlying the various processes contributing to the interactions between marine ecosystems and human health



Sources: Courtesy of Prof. J. I. Allen; Allen, 2011; Moore and others, 2014.

The attainment of such a vision requires an appropriate international interdisciplinary forum or panel. However, a one-off report on ocean and human health from the High Level Panel for a Sustainable Ocean Economy (Ocean Panel) could provide the example for a potential way forward (https://oceanpanel.org/publication/ocean-human-health).

Such a panel/forum could prioritize:

1. The failure of numerous international agreements to prevent progressive loss of marine biodiversity and collapse of several marine ecosystems with implications for human health, and explore strategies to reverse this situation;
2. Effective protection of coastal communities from natural threats, including flooding and tsunamis/hurricanes;
3. Knowledge of interactions between natural and anthropogenic stressors that impact ocean and human health;
4. Most issues are associated with both benefits and threats – it often depends on the context as to whether we sacrifice a benefit to remove a threat or accept a threat to gain a benefit: Who then decides and on what basis?
5. Awareness of health professionals and documentation of environment-related illnesses;
6. Exploring potential unique medicines and other natural marine products, while ensuring sustainable use and protection of marine life and habitats (Papon and others, 2022);
7. Developing an integrated modelling capacity for predicting environmental impacts on human health (see figures XI and XII; Allen, 2011; Moore and others, 2014).

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Chapter 3
Human well-being

Key points

- The intrinsic value of oceans extends beyond economic benefits, as oceans enrich human life through cultural, recreational and ecological contributions.
- Oceans have many non-economic benefits, including cultural and ecological value.
- Non-market valuation methods are used to quantify the intangible benefit of oceans, including clean air, biodiversity and recreational spaces.
- Marine environments can boost subjective well-being and provide mental health benefits, such as stress relief and emotional resilience, which are central to the blue health concept.
- Oceans support cultural practices, spiritual connections and knowledge-sharing across generations, which can strengthen identities and resilience within communities.
- Ocean-based recreational activities benefit physical and mental health, and foster social bonds, community cohesion and an appreciation for the environment.
- Climate change, pollution and resource depletion are potential risks to marine ecosystems and human well-being.
- By sustaining fisheries, livelihoods, cultural heritage, social cohesion and intergenerational well-being are preserved.

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1. Introduction

The present chapter contains an overview of the various ways that oceans contribute to human well-being and an exploration of the interplay between ocean ecosystem health and aspects of human prosperity. Although the economic advantages offered by oceans to global and local communities are substantial, the present chapter is focused on the non-economic benefits that contribute to well-being beyond measurable financial value (Koundouri and Giannouli, 2015). An assessment of economic benefits is covered elsewhere in the third *World Ocean Assessment* (see, for example, subsect. 5A, chaps. 4, 6, 7 and 9), thereby enabling the present chapter to be focused on the intrinsic value of oceans, including its cultural, mental health, recreational and community-supporting roles.[1]

Through welfare economics and non-market valuation, such as the contingent valuation and travel cost methods, the present chapter serves to illustrate how quantifying non-economic benefits informs sustainable policymaking. Various aspects, such as the concept of blue health, are explored, and the mental and physical health advantages that arise from proximity to marine environments are highlighted (see also subsect. 5A, chap. 2). Community-focused case studies show the essential role played by oceans in supporting cultural identity, heritage and social cohesion, thereby underscoring the need for inclusive, sustainable ocean management (Anderson and others, 2022; Brondizio and others, 2019). Confronting threats such as climate change and pollution is crucial to maintaining non-economic benefits, and a wide-ranging governance approach would help to sustain the critical connections between ocean health and human well-being for future generations.

2. Welfare economics of non-market valuation

Welfare economics can be used to examine the value provided by oceans beyond monetary metrics and can reveal critical aspects of non-market valuation. Several non-market goods and services, such as clean air, biodiversity and recreational spaces, play an important role in human well-being (Millennium Ecosystem Assessment, 2005). Nevertheless, they are difficult to measure in traditional economic terms, as they are not traded in markets. It is thus necessary to find ways to capture the wide range of non-market benefits, which contribute not only to global ecological balance, but also to quality of life, cultural heritage and community cohesion.

Several methods, such as the contingent valuation method (a survey-based willingness to pay approach; see, e.g., Carson, 2012), the travel cost method (value from travel expenses; see, e.g., Ward and Beal, 2000), choice experiments (hypothetical choice modelling; see, e.g., Louviere and others, 2000), hedonic pricing (property price analysis; see, e.g., Rosen, 1974) and the replacement/restoration cost method (cost to restore ecosystems; see, e.g., Freeman, 2003), can be used to capture various environmental aspects.

Among those methods, the focus in the present chapter is on the contingent valuation and travel cost methods, as they are well suited for capturing the intangible benefits of ocean ecosystems.

Contingent valuation method. Contingent valuation is a survey-based technique that serves to assess people's willingness to pay for preserving or restoring environmental goods. The approach is instrumental in gauging public support for conservation frameworks, particularly for intangible goods, such as ocean habitats or biodiversity, where direct market prices are absent. As outlined by Carson (2012) and Hanemann (1994), contingent valuation is useful when assessing non-market assets, such as ocean ecosystems. Examples include survey respondents indicating their willingness to pay to protect marine biodiversity and to evaluate the value of experience of ocean education (Lee and Kim, 2024). The approach provides a monetary estimate of the perceived worth of ecosystems.

Travel cost method. Through the travel cost method, economic values associated with recreational sites are estimated by analysing the expenses incurred by visitors to access such sites (Padilla and Diswandi, 2024; Parsons, 2003; Ward and Beal, 2000). When applying the method to marine parks or coastal areas, travel costs can be used as a proxy for the value that visitors attach to the recreational

[1] Further details can be found in Termansen and others (2022).

usage of ocean spaces. Visitor costs, such as access fees for marine reserves, represent the recreational value of those sites, contributing to the understanding of how recreational goods contribute to the overall valuation of ocean ecosystems (Ward and Beal, 2000).

Market valuation contributes to environmental cost-benefit analysis by measuring the benefits of ecological services against their potential costs (Boardman and others, 2017). Non-market environmental values can be incorporated into cost-benefit analysis to inform environmental decision-making (Pearce and Turner, 1990).

The valuation of sustainable fisheries and ocean-based livelihoods is an important dimension that relates to these approaches. For many coastal communities, oceans are not only ecosystems to be conserved, but also vital sources of income, nutrition and cultural identity. It is thus important to acknowledge the role of fisheries in supporting well-being, which is particularly true in low-income or food-insecure regions, as doing so ensures that valuation frameworks reflect the full spectrum of ocean-related benefits. Moreover, in terms of policy, acknowledging the role of fisheries in supporting well-being is particularly relevant for designing inclusive policies aimed at balancing conservation goals and coupling them with the needs of those who directly depend on marine resources for their living.

Using these methods, policymakers can assess non-market values and thus recognize ocean benefits, such as climate regulation, biodiversity conservation and public health and nutrition, which might otherwise be underestimated or overlooked.

Case studies further demonstrate how non-market valuation affects marine policy (Koundouri and others, 2023a, 2023b), and discuss how valuations influenced the establishment of marine protected areas (MPAs) and guided decisions on resource allocation and conservation (Spash, 2000; Costanza and others, 1997). By quantifying the benefits derived from oceans, valuation methods can inform policies aimed at sustaining marine ecosystems, thereby ensuring that oceans continue to support human welfare.

Another important consideration regarding the intrinsic nature of ocean resources is their public good characteristics. As in the case of every public good, oceans are non-excludable and non-rivalrous, meaning that access cannot easily be restricted and that one person's enjoyment does not diminish that of another. It is also essential to highlight that oceans often exhibit traits of common-pool resources, rather than purely public goods, making them vulnerable to overuse or congestion if not carefully managed. All these complexities are explored in Ostrom (1990) and Samuelson (1954), who argue that such goods complicate valuation efforts, especially when trying to establish boundaries for willingness to pay or equitable resource allocation.

To complicate matters further, policymakers must also consider intergenerational equity (see subsect. 5B, chap. 5), which involves ensuring that ocean resources benefit both present and future generations and that their intergenerational nature is taken into account when using them. It is important to preserve the ocean in order to allow future generations to enjoy their substantial non-use values. These values are particularly challenging to measure, as they reflect primarily intangible and non-measurable benefits, such as cultural heritage and intergenerational welfare. Survey techniques can be used to estimate the individual value of the existence or preservation of ocean ecosystems (Krutilla, 1967; Loomis, 2000; Halkos and others, 2024). By developing methods to capture the intangible worth of oceans, from recreational and health benefits to climate regulation and cultural significance, policies can honour the essential enduring role of the ocean in a world facing challenges.

3. Subjective well-being

Drawing on the insights from welfare economics and non-market valuation, the focus below is on subjective well-being in order to explain how ocean environments can be a source of well-being for individuals and support for community sustainability.

Welfare economics as a field is focused on two aspects: efficiency (maximizing total benefits) and equity (ensuring distributional fairness) (Pigou, 1920). A key concept in this context is subjective well-being, which measures self-reported life quality, including factors such as life satisfaction, happiness and mental health. Studies by Kahneman and Krueger (2006) underscore how important environmental conditions are in shaping subjective well-being, illustrating how positive physical spaces can foster happiness and alleviate negative emotions.

The natural characteristics of marine environments create unique psychological and emotional experiences that contribute to people's well-being. Moreover, oceans often carry important spiritual and cultural value, adding another layer to their contribution to subjective well-being. Taken together, these considerations highlight the critical role that ocean environments play in improving mental health and overall happiness, positioning them as key contributors to both individual welfare and broader community resilience.

The wide range of health benefits associated with spending time in or near water bodies, especially marine environments, is captured by the concept of blue health. Researchers have found that proximity to blue spaces can significantly affect mental and physical health and thus offer opportunities for both active and passive engagement with nature. For example, Gascon and others (2017) argue that time spent near blue spaces is associated with stress reduction, enhanced mood and increased opportunities for physical activity. All these benefits are most noticeable in coastal communities, where activities such as swimming, walking on the beach and being near water can reduce anxiety, promote cardiovascular health and help to boost emotional resilience (Kronsted Lund and others, 2023).

Marine environments are especially restorative because their sensory qualities, such as natural sounds, open horizons and a calming atmosphere, help to direct and refocus attention. Owing at least in part to the natural sounds, vastness of open water and the impression of a relaxing atmosphere associated with these bodies of water (Völker and Kistemann, 2011), researchers have highlighted that blue spaces, such as oceans and rivers, may offer health benefits beyond those provided by green spaces, including by triggering nurturing physiological responses, such as decreased blood pressure and cortisol levels, which promote the reduction of stress (Gascon and others, 2017). For that reason, oceans can serve as natural refuges for people and communities alike by providing respite from the pressures of modernity and urban living.

Long-term well-being may also be supported by the physical activity benefits associated with blue health environments (White and others, 2020). Individuals living in coastal areas tend to engage more frequently in outdoor activities such as walking, swimming and recreational sports – behaviours that are linked to improved physical health outcomes. In that context, variation in access to coastal environments can act as a catalyst for blue health by highlighting how proximity to water facilitates active lifestyles and by revealing potential inequalities in opportunities for such engagement across communities. Such dynamics are particularly relevant for community well-being, as regular interaction with coastal spaces can contribute to healthier behavioural patterns, strengthen local identity and support place-based social cohesion. Moreover, public visibility of everyday coastal practices, such as walking along the shoreline, can reinforce awareness of the physical and psychological benefits associated with blue spaces. At the household level, shared ocean-related activities may further promote intergenerational interaction, foster stronger family bonds and cultivate respect for coastal cultural traditions.

The influence of marine environments on mental health is an important factor that goes beyond the physical benefits of being close to the ocean. Proximity to water and other natural settings is consistently linked to lower stress levels, improved moods and better cognitive performance. Living near green and blue spaces is associated with lower psychological distress and higher life satisfaction, according to a number of researchers (e.g. White and others, 2013). Oceans often provide a peaceful setting that evokes feelings of calm, which can reduce anxiety and depression. Ocean environments also provide relief from the noise and cognitive demands of cities, thereby promoting mental renewal.

Furthermore, Pearson and Craig (2014) highlight the specific mental health benefits that can be derived from outdoor environments, including oceans. They argue that natural spaces encourage mindfulness, which can, in turn, help individuals to focus on the present moment and temporarily distance themselves from stressors. That shift of attention is crucial for mood regulation and helps to build resilience against mental fatigue.

In the light of the substantial benefits that oceans provide for subjective well-being and blue health, there are strong policy arguments for ensuring equitable access to coastal areas. Local governments and urban planners can advance that aim by prioritizing the development of accessible blue spaces, especially in areas where communities face socioeconomic barriers to such environments.

At the same time, it is important to acknowledge that expanding access to blue spaces for recreational purposes, such as tourism and leisure, may conflict with the livelihood activities of local coastal communities.

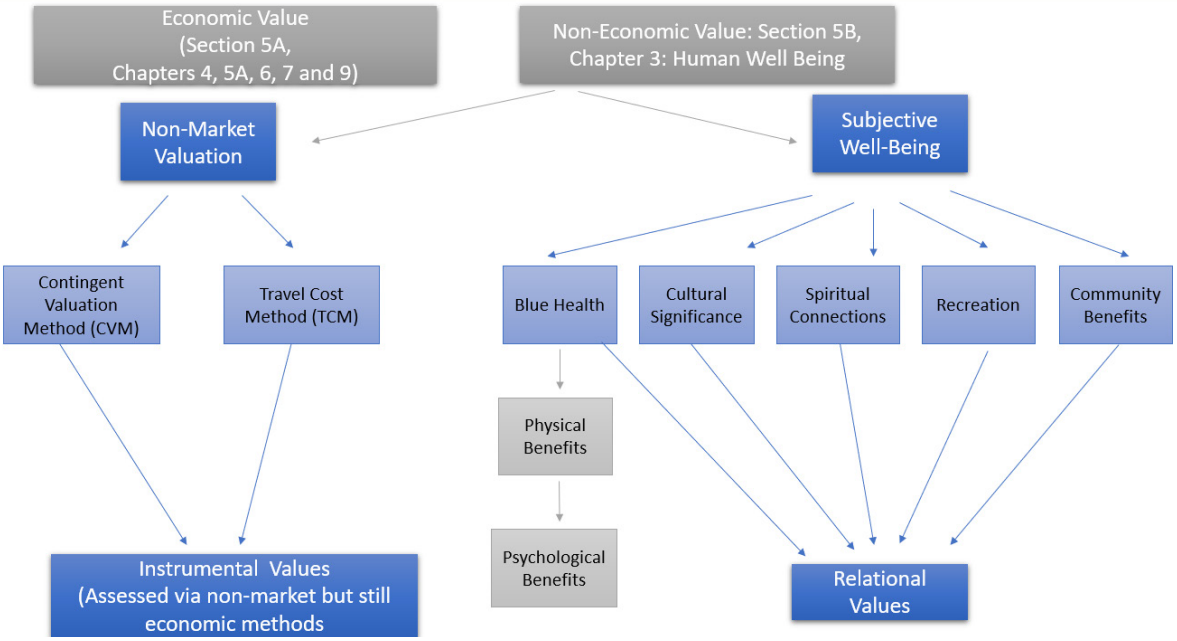
For example, increased beach access or tourism infrastructure can disrupt traditional fishing zones or compromise ecosystem health. Such disruptions can affect the well-being of those who rely on the ocean for their livelihood, income and cultural practices. That is a critical concern that policymakers must factor into their decision-making processes. They must carefully balance the recreational and economic uses of marine spaces and ultimately ensure, on the one hand, that blue health benefits are equitably distributed, and, on the other hand, that local fishing communities are not marginalized in the pursuit of tourism-driven well-being.

Co-management approaches and stakeholder engagement can help to mitigate such conflicts by integrating both local needs and environmental sustainability into planning. In addition, measures aimed at facilitating access to coastal areas or maintaining affordable public beach access can help to strengthen mental and physical health across populations, while at the same time protecting local production.

In conclusion, there is a need to preserve the health of ocean ecosystems in order to sustain their therapeutic benefits. Enhancing the protection of coastal and marine ecosystems against pollution, habitat degradation and climate impacts will be crucial to maintaining their natural contributions to mental health and well-being. Doing so will involve limiting coastal development, ensuring financial support for MPAs and developing long-term solutions aimed at reconciling climate change responses with the preservation of ocean landscapes.

Figure I

Conceptual framework for the relationship between oceans and human well-being



Source: Prepared by the writing team.[2] *Note*: To illustrate the relationship between oceans and human well-being, two main pathways are highlighted: non-market valuation and subjective well-being. The graphic is aligned with the values assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

[2] Although market-based or non-market-based economic valuation methods play a key role in capturing instrumental values, especially for decision-making in environmental policy, the present chapter does not contain details of the full range of economic valuation techniques (see the various chapters of subsection 5A). The focus is on emphasizing subjective well-being and non-economic dimensions that complement conventional valuation approaches.

Instrumental values refer to the usefulness of nature for the achievement of human ends. They are typically expressed through benefits such as provisioning, regulating and cultural services. In figure I, they are assessed through non-market valuation tools, such as the contingent valuation and travel cost methods, while remaining rooted in economic frameworks. This approach is aligned with the IPBES values assessment, which frames instrumental values as those that view nature in terms of its capacity to satisfy human preferences, whether directly (e.g. food, water and recreation) or indirectly (e.g. ecosystem regulation).

Relational values, by contrast, describe the meaningful relationships that individuals and communities have with nature, such as cultural identity, place attachment or responsibilities to protect ecosystems. These values are especially relevant to concepts such as community well-being, spiritual connections and cultural significance. IPBES highlights relational values as essential for understanding how people define a good life in connection with nature, extending beyond utility or market proxies.

4. Societal dimensions of ocean-human interactions

Cultural significance

For millenniums, oceans have been a source of cultural meaning – an important part of the stories, identities and traditions that have shaped countless societies throughout human history. Their role is multifaceted; they are not only intertwined with livelihoods in coastal communities, but also contribute to cultural expressions and help to maintain intangible heritage. There are several aspects to consider that are linked to maritime heritage, such as various practices, beliefs and customs that have evolved around the sea, from fishing traditions to artistic expressions (see also subsect. 5A, subchaps. 1A and 1B), all of which are living proof of how oceans shape the lives and identities of those who live near them. The vital role played by oceans in supporting cultural practices, the preservation of intangible heritage and intergenerational knowledge transfer is presented below.

Maritime heritage encompasses a vast array of cultural expressions, such as traditional fishing techniques, navigational knowledge, storytelling and festivals that celebrate the connection between communities and the sea. For several coastal societies, oceans have been central to cultural identity, offering material and symbolic resources. Prominent examples include traditional maritime songs, dances and rituals that are expressions of local identity and reinforce the importance of ocean conservation. Coastal communities often incorporate such expressions into local festivals and ceremonies, celebrating the ocean as a life-giving force (Berkes, 2012).

Food culture is another important aspect, as oceans provide culturally significant food sources that are integral to culinary traditions (see also subsect. 5A, chap. 1). Traditional seafood dishes, for example, can reinforce community bonds and strengthen the connection between people and the ocean. Access to culturally relevant food resources therefore helps to sustain dietary customs and preserve the cultural heritage of coastal societies. Beyond their cultural significance, such foods offer nutritional value and are essential for the overall health and well-being of coastal communities (see also subsect. 5B, chap. 2).

In addition, small-scale fisheries are a principal vehicle for nutrition, livelihoods and cultural identity for coastal communities, which highlights the deep social and economic connection of those communities with the ocean. Aside from their economic contribution, such fisheries support biodiversity preservation, reinforce community identity and sustain intangible cultural practices that have been passed down for centuries (see also subsect. 5A, subchaps. 1A–1D).

The transfer of traditional knowledge is essential in preserving cultural practices associated with the ocean. Cultural knowledge includes ecological wisdom and spiritual beliefs tied to the sea and is often passed down through generations. Intergenerational equity is therefore a vital aspect of such transfer; each generation inherits both the responsibility and privilege of caring for the ocean (Poe and others, 2014). For example, knowledge about marine ecosystems, seasonal fish patterns and sustainable harvesting techniques supports both ecological health and cultural continuity (Berkes, 2012).

The considerations presented above highlight the importance of intergenerational equity at a time when ocean ecosystems are facing increasing environmental threats. Ensuring that future generations have access to healthy oceans is not only an ecological responsibility, but also a cultural one. When knowledge transfer is disrupted, whether through environmental degradation, restricted access to coastal areas or the loss of language and practices, the cultural connections between communities and the ocean risk being lost. Policies aimed at supporting traditional knowledge transmission and promoting sustainable ocean management are therefore crucial for preserving cultural heritage (Koundouri and others, 2023b).

Spiritual connections

Ecosystem services are increasingly recognized as an essential aspect of human well-being. The concept of ecosystem services refers to the broad range of benefits provided by natural systems (Millennium Ecosystem Assessment, 2005). Cooper and others (2016) report that the Millennium Ecosystem Assessment contains 335 instances of the word “spiritual”. According to Koundouri and others (2025), spiritual ecosystem services can be defined as a subset of cultural ecosystem services that provide intangible benefits to human well-being, including inspiration, connection to nature and a sense of place.

Cultural, religious and individual beliefs are often intertwined with the services provided by the spiritual ecosystem, from individual experiences and feelings connected to nature to subjective beliefs and a sense of sacredness. Spiritual ecosystem services offer numerous benefits, including the beauty and wonder of natural

landscapes and the symbolic and religious significance of ecosystems.

Associated literature

The reviewed literature on the economics of the spiritual values of ecosystem services emphasizes that conventional economic frameworks must be rethought in order to fully capture the variety of benefits offered by ecosystems.

Although challenges remain, advancements in methodologies and a growing recognition of the importance of spiritual values offer opportunities for more comprehensive and inclusive assessments of ecosystem services. By understanding and valuing spiritual values, ecosystem services can be better protected and managed. Ecosystem services are often difficult to quantify and measure, making their assessment challenging. The economic measurement of spiritual ecosystem services remains open to debate. While traditional economic valuations are often focused on tangible, market-based benefits (e.g. food, water and timber), the intangible, non-market benefits, including spiritual and cultural aspects, are becoming more widely recognized. These values, which are frequently rooted in cultural, religious and personal beliefs, as well as in human-nature ties, are essential for understanding how ecosystems contribute to overall societal well-being, but they are frequently disregarded in decision-making processes (Brander and others, 2024; Duha and others, 2023).

The need for a thorough grasp of spiritual ecosystem services has increased, as nature-based solutions for addressing social issues gain broader recognition. The significance of integrating spiritual values into decision-making processes is becoming more widely acknowledged by Governments and enterprises. By including those values in conservation planning, ecosystems can be safeguarded and managed in a way that reflects cultural and spiritual requirements. Economic assessments can support informed decisions regarding resource allocation, development and land use. Recognizing the significance of spiritual values can also foster increased public involvement in environmental issues. A more thorough evaluation of the advantages and disadvantages of development projects can be obtained by including spiritual values in policy. Promoting community participation in conservation initiatives can be greatly aided by spiritual principles.

Most existing studies draw on qualitative valuation methods. In fact, although traditional economic valuation methods, such as contingent valuation and hedonic pricing, are often used to assess tangible benefits, such methods may not fully capture the spiritual values of ecosystem services. Assigning monetary values to these services is a complex and often controversial task. Economic valuation is fundamental to decision-making and policies related to resource allocation; however, the process of attaching monetary value to intangible and subjective benefits can be very complex. Spiritual ecosystem services are inherently subjective and often difficult to express in quantitative terms, which makes it challenging to develop standardized assessment methods. The value and significance of spiritual ecosystem services vary across cultures, religions and individual experiences. As a result, valuation methods must be flexible and adaptable to diverse contexts.[3]

It is important to note that the majority of ecosystem services linked to spirituality are located in coastal and marine settings or places that are connected to water (Nevzati and others, 2023). In any case, spiritual ecosystems are unquestionably regarded (and quantified) as valuable because they consistently convey well-being, welfare and benefits, even when they are declining and even though they are defined in multiple ways. Their benefits include inspiration, freedom, a sense of transcendence and a connection to nature (such as oceans or forests). They may also carry a sense of sacredness, either because they are located in nature or because, in urban settings, they are symbolically connected to ideas of creation or humanity's origins, often through myths and shared traditions. In this way, places acquire meaning

[3] Scholars have, however, explored various valuation methods. For example, qualitative methods, including interviews, focus groups, expert elicitation and assessment, local community involvement and participatory mapping, can provide insights into the subjective experiences, perceptions and beliefs associated with ecosystems. Integrated multidisciplinary assessment methods bring together cultural, ecological and economic perspectives to assess the full range of ecosystem services, including provisioning, regulating and cultural services. Integrated multidisciplinary assessment methods that are enabling new approaches to assessing spiritual ecosystem services include ethnographic studies (that can provide insights into the cultural significance of spiritual ecosystem services within specific communities), spatial analysis techniques to identify areas that are important for spiritual ecosystem services provision, studies combining qualitative and quantitative methods, benefit transfer, remote sensing and geographical information systems.

not only through their physical characteristics, but also through the cultural and spiritual interpretations attached to them. More broadly, values represent individual or collective evaluations of benefits, whether these are linked to specific locations or to the environment as a whole.

Recent studies have begun to integrate both quantitative and qualitative data-gathering techniques, such as interview surveys and case study analyses, in order to identify and measure the spiritual importance ascribed to the attributes of specific ecosystems. Those evidence-based approaches complement the reflective views contained in the present chapter while offering certain metrics or narratives that clearly depict how spiritual value converges with ecosystem services. A notable example is the study by Cooper and others (2016), which combined both survey data and in-depth interviews to explore how individuals perceive and value the spiritual and aesthetic qualities of ecosystems. This mixed-methods approach provided quantitative indicators, such as the reported frequency and degree of spiritual significance, and qualitative insights into participants' personal and cultural connections with natural landscapes.

Quantifying spiritual values, however, presents unique challenges. Spiritual values are highly subjective and vary across individuals and cultures. They are not traded in markets, making it difficult to assign monetary value. Moreover, survey-based methods may be subject to biases, such as hypothetical bias or anchoring effects. The monetization of spiritual values can raise ethical concerns with regard to commodifying intangible aspects of the human experience. Nevertheless, understanding the economic value of spiritual values can inform policy decisions and resource management. By understanding the challenges and opportunities associated with assessing spiritual ecosystem services, researchers can develop more effective methods for assigning value and protecting important ecosystem benefits (Cheng and others, 2019).

Methodological approaches to assessing spiritual ecosystem services

In order to assess spiritual ecosystem services, researchers often rely on qualitative and participatory approaches, reflecting the intangible nature of spiritual values. A notable example is the study by Sangha and others (2018), which utilized a value transfer approach in northern Australia, where Indigenous communities derive spiritual and well-being benefits from coastal and marine resources. According to the study, spiritual ecosystem services can be captured by understanding the cultural narratives and symbolic meanings attached to natural resources, a perspective that is especially relevant for Indigenous communities. Similarly, Klain and Chan (2012) interviewed marine resource users in British Columbia, Canada, and found that the ocean holds strong spiritual significance and plays a central role in shaping both personal identity and the shared sense of belonging within the community.

A shared feature of those studies is their participatory orientation, consistent with the methods used by Bryce and others (2016), who assessed spiritual ecosystem services at broad scales using hedonic measures of subjective well-being. They measured values, including sense of place, belonging and intergenerational continuity, through surveys and interviews. Such approaches shed light as to how spiritual ecosystem services contribute to subjective well-being, as participants also emphasize their relationships with particular natural places that evoke feelings of reverence and respect for nature (Keniger and others, 2013).

Challenges in quantifying spiritual ecosystem services

The quantification of spiritual values presents a unique set of challenges due to the subjective and culturally dependent nature of those values. Unlike market-based ecosystem services, spiritual values are often not traded in markets, making them difficult to measure through traditional economic methods (Cooper and others, 2016). Studies, including those by Sangha and others (2019) and Brown and Hausner (2017), therefore rely on qualitative data to gauge the importance of spiritual ecosystem services, using participatory mapping and interviews to capture non-material benefits. The application of monetary valuation can lead to ethical concerns about the commodification of spiritual experiences. For example, applying the contingent valuation method to willingness to pay assessments may not fully capture the intrinsic value of spiritual landscapes, as motivations for conservation can be driven by cultural, existence or bequest values, rather than economic incentives (Klain and Chan, 2012).

Another significant challenge lies in the lack of a unified definition of spiritual ecosystem services, as there are diverse cultural interpretations of spirituality in the context of nature. Various studies highlight the variance in spiritual ecosystem services definitions and the corresponding methodologies, thereby further complicating a standardized assessment approach (Bryce and others, 2016). Spiritual values also extend beyond individual

experiences to reflect shared, collective values, suggesting that spiritual ecosystem services assessments may need to incorporate more community-oriented perspectives in order to fully capture their importance (Irvine and others, 2016).

Recreation

Exercising in the ocean, including swimming, surfing and diving, is hugely beneficial to our physical and mental well-being. Such locally rooted activities not only enhance individual well-being, but also reflect sea-based cultures in which the ocean shapes everyday life. Ocean-based recreation is also recognized as a way of supporting the right to play, which is vital for natural childhood development, facilitates learning and strengthens the sense of connection with the marine environment (Keniger and others, 2013) (see also subsect. 5A, chap. 2).

In addition, recreation plays a cultural role, as it strengthens community bonds and serves as a source of identity. In that sense, ocean-based activities extend beyond leisure to include the right to culture and education, fostering an appreciation for marine ecosystems that lasts into adulthood.

Maintaining a healthy ocean is also integral to sustaining livelihoods that rely on recreational tourism (see also subsect. 5A, chap. 4), which is a major economic driver for many coastal areas. When marine environments are well preserved, they attract visitors seeking unique ocean experiences, thereby generating income for local communities. It should be noted that this relationship is mutual; for recreation to thrive, the health of marine ecosystems must be prioritized. For example, the experience of Miskito divers – traditional fishers who also engage in diving tourism – illustrates this mutual dependency. Any pollution or degradation of marine habitats would directly affect their livelihoods, which reinforces the need for sustainable practices that balance human activity with ecosystem conservation (Sangha and others, 2019).

Although public attention has generally been focused on the physical wellness benefits of oceans, their mental health benefits must be equally acknowledged. Studies show that time spent near water is associated with reduced stress and anxiety and enhanced mental clarity (Gascon and others, 2017). The ocean serves as a place of mindfulness and restoration for many people, helping them with stress-related ailments. Public health policies that encourage recreation in or near the ocean can contribute to both mental health and physical fitness.

Healthy ecosystems, maintained through environmentally friendly leisure activities and policies aimed at safeguarding the ocean, support communities and provide opportunities for future generations to use the ocean sustainably for health, recreation and economic opportunities without harming local production and contributing to unsustainable growth.

Community benefits

Ocean ecosystems play a vital role in promoting cooperation at the community level, shaping social identities, supporting community welfare and fostering sustainable development.

There are a variety of relevant social events in which people can participate, including beach clean-ups, fishing events and ocean-related celebrations. Through such events, individuals are made aware of the importance of caring for the ocean while also practising sustainability. In addition to their recreational and social value, such events also educate the participants on ocean conservation and promote behaviours and habits that ensure that ocean ecosystems continue to thrive for future generations (Irvine and others, 2016). Through hands-on engagement, community members feel a shared sense of responsibility for the ocean, thus leading to lasting support for conservation efforts.

Furthermore, there is a need to acknowledge the immeasurable value of the sea. The sea not only provides us with countless opportunities for recreation and cultural experiences, but also contributes significantly to the well-being of communities. There are also economic aspects, as many people in coastal regions depend on the sea for their sustenance, including through fishing or ocean-based tourism. Such activities generate large economic benefits and contribute to the welfare of such communities.

Eco-friendly sustainable tourism practices can help communities to strike a critical balance between financial growth and marine habitat protection. Such practices help to build resilience and offer communities an anchor to develop sustainable ways of life that support the global need to care for the health of ocean ecosystems (Sangha and others, 2019).

The ocean is particularly important in coastal regions and plays a key role in cultural identity and heritage. The ocean is a resource and a symbol of cultural identity for many Indigenous Peoples around the world, not only acting as

an essential service but also enabling them to participate in traditions that are passed down from generation to generation. Engaging young people in local communities in ocean literacy activities helps to reinforce their sense of cultural identity while also instilling them with values associated with environmental stewardship, illustrating the need for a healthy ocean to support overall well-being and maintain cultural continuity (Gould and others, 2015).

Social capital can also be viewed as a vital aspect that contributes to the resilience and sustainability of coastal communities, fostering trust, cooperation and shared responsibility towards ocean conservation. Strong community bonds stimulate cooperation in marine resource management, enabling traditional knowledge and collective action to support long-term sustainability (Pretty and Smith, 2004). Areas that are cosmopolitan and developed in terms of social capital usually have stronger local governance systems and active community participation in environmental programmes aimed at promoting the stewardship of marine ecosystems (Aldrich and Meyer, 2015). In addition, social networks enable communities to mobilize resources, share information and adjust to environmental changes, especially climate-related threats to fisheries and coastal livelihoods (Adger, 2003). The strengthening of social capital through inclusive decision-making processes and participatory conservation frameworks can promote environmental conservation and community livelihood enhancement for a more integrated approach to ocean sustainability.

Developing sustainable policies is crucial to fully harnessing the social, economic and cultural benefits. Actions aimed at promoting sustainable fishing, responsible tourism and community-based conservation frameworks can help to preserve marine ecosystems and support local economies. By further integrating community perspectives into conservation and resource management policies, the needs of local populations are addressed, thereby fostering a stronger connection between community welfare and ecosystem health (Chan and others, 2016).

5. Challenges and threats

In recent years natural ecosystems, such as marine environments, have been confronted with a large number of risks that compromise the health of human beings and the sea itself. The Intergovernmental Oceanographic Commission gives a detailed discussion of the challenges (2022, 2024). Related issues and suggested actions can be found in the second *World Ocean Assessment* (chap. 27). The major challenges affecting the survival, development and well-being of many communities and species are driven by factors such as pollution, climate change and environmental degradation. Ensuring the sustainability of the increased exploitation of the environment and the pace of development is essential in order to better deal with and, in the long term, eliminate such concerns.

Climate change is perhaps the most severe threat to oceanic systems. Increasing temperatures are accelerating and intensifying ocean acidification, thereby damaging coral reefs and marine life (Hoegh-Guldberg and others, 2017). As marine species move to colder waters, local ecosystems are weakened, which poses significant risks to coastal societies, particularly those that rely heavily on fishing.

Another major threat to the ocean is pollution. In particular, plastic waste and chemicals have a severe impact on marine life and water quality, and it is increasingly being reported that microplastics have infiltrated the food chain, affecting fish and shellfish consumed by humans, which poses health risks to people (Jambeck and others, 2015). Similarly, agricultural run-off, laden with nutrients, causes eutrophication in coastal areas, leading to algal blooms that deplete oxygen and create dead zones. In order to mitigate pollution, strategies such as waste management reforms, stricter regulations on plastic production and public awareness campaigns are essential.

Resources are being depleted at unprecedented rates, raising serious challenges as new threats emerge (see also subsect. 5A, chap. 3). This has recurred during economic history. Recent instances of unsustainable resource extraction have put more pressure on ocean ecosystems. Fish stocks are declining as a result of rising demand for seafood, which, in turn, reduces marine biodiversity. This depletion not only affects marine life, but also poses risks to food security and the economies that rely on fishing. In that regard, adopting sustainable fishing practices, investing in aquaculture and cultivating international cooperation are necessary for healthy fisheries and sustainable fish stock control (Pauly and Zeller, 2016).

To address those challenges, comprehensive strategies, including conservation efforts, policy reforms and community involvement, are needed. Global frameworks, such as the Paris Agreement, along with local efforts, including coastal restoration projects, demonstrate the need for integrated approaches to protect ocean health. The United Nations Decade of Ocean Science for Sustainable Development Vision 2030 white papers contain in-depth discussions of several challenges and suggested solutions. By tackling climate change, minimizing pollution and encouraging sustainable resource use, ocean ecosystems can be preserved and the well-being of both current and future generations can be ensured.

6. Case studies

Several case studies related to various topics addressed in the present chapter are presented in figure II below. In particular, they explore aspects such as marine resource management, fisheries management, recycling waste fishing nets, cultural ecosystems, community-based coral reef management, and sacred sea rituals and marine conservation. Figure II presents an overview of the context, challenges and action undertaken. A more detailed examination of Indigenous and local community knowledge can be found in subsection 5B, chapter 8.

7. Conclusion

The present chapter highlights the extensive contributions of ocean ecosystems to human well-being, ranging from economic value to non-market benefits such as spiritual, cultural and recreational services. Non-market valuation, despite its challenges, remains crucial to understanding and quantifying the non-monetary value of oceans, which can enable informed policy decisions that support both human and environmental health. Subjective well-being is closely linked to the therapeutic and restorative qualities of marine environments, which reinforces the significance of accessible blue spaces for mental and physical health. Ocean ecosystems play an irreplaceable role in supporting cultural practices, traditional knowledge and intergenerational heritage. Preserving marine resources for small-scale fisheries and coastal communities is very important to safeguard their livelihoods, cultural heritage and social unity. Many of those communities actively engage in conservation efforts, as protecting their fisheries helps to secure economic stability, while also preserving their traditions, cultural identities and overall well-being across generations through community-based management and stewardship.

The case studies illustrate how different communities interact with, and depend on, ocean resources, often employing innovative strategies to balance conservation with socioeconomic needs. However, growing environmental challenges, such as climate change, pollution and resource depletion, pose severe risks to those benefits, underscoring the need for robust policy frameworks and community-driven conservation. Integrating cultural, economic and ecological perspectives into ocean management policies helps to ensure that oceans continue to support human well-being, cultural heritage and sustainable development for future generations.

Figure II

Community-led ocean conservation: case studies in sustainable marine management

Marine Resource Management Sangha and others (2019)	Fisheries Management Carothers, 2015	Recycling Waste Fishing Nets
Context The Torres Strait Islanders are an Indigenous group in northern Australia. They have a deep cultural, economic, and survival-based connection to the ocean. Marine resources are central to their traditions, livelihoods, and identity. **Challenges** Climate change and rising sea levels threaten local fish stocks and fishing areas. These environmental changes put their food security and traditional way of life at risk. **Action** The community has adopted co-management strategies blending traditional ecological knowledge with modern science. These efforts support sustainable resource management and adaptability to environmental changes. The **Torres Strait Regional Authority (TSRA)** collaborates with community leaders to integrate Indigenous methods into marine policy.	**Context** Many coastal towns in Alaska depend on fishing for both employment and cultural identity. Fishing is vital for local economies and food security. **Challenges** Climate change has significantly reduced fish populations, impacting food supply and economic stability. **Action** Alaska has implemented community-based fisheries management, involving local participation in decision-making. The **Alaska Community Development Quota (CDQ) program** allocates fisheries quotas to coastal towns. This program promotes sustainable fishing, job creation, and marine conservation.	**Context** Ghost gear threatens marine ecosystems, entangling species and damaging habitats. 640,000 tons of fishing nets are abandoned yearly. **Challenges** High labor costs and low financial incentives hinder net recovery efforts.

Cultural Ecosystem Services Vave and others (2024)	Community-Based Coral Reef Management Cinner and Aswani (2007)	Sacred Sea Rituals and Marine Conservation Foale and Macintyre (2000)
Context **Cultural ecosystem services (CES)** in Fiji's **Funerary Protected Areas (FPAs)** integrate spirituality with conservation. **Clan-specific water practices (CPWB)**, including funerals and rituals, reinforce cultural identity. **Challenges** External influences threaten **Indigenous knowledge** and **social cohesion**. CPWB practices are often **overlooked in conservation planning**, risking cultural displacement. **Action** **Vave and others (2024)** call for integrating FPAs into conservation strategies. **Vave (2022)** identifies key CPWB practices, emphasizing their role in **ecological and cultural preservation**.	**Context** Coral reefs provide critical ecosystem services, supporting marine biodiversity, fisheries, and coastal protection. In Indonesia, many coastal communities rely on reefs for food security, livelihoods, and cultural practices. **Challenges** Climate change, coral bleaching, overfishing, and destructive fishing practices threaten reef ecosystems. Loss of coral reefs reduces fish stocks, affecting food security and local economies. **Action** Community-based coral reef management (CBCRM) initiatives empower local fishers to monitor, protect, and sustainably manage reef ecosystems. Programs like the Locally Managed Marine Areas (LMMAs) integrate Indigenous knowledge with scientific conservation to establish no-take zones, reef restoration projects, and sustainable fishing practices. These efforts restore marine biodiversity, enhance fisheries, and strengthen cultural and social resilience among coastal communities.	**Context** In Papua New Guinea (PNG), coastal communities maintain deep spiritual and cultural ties to the ocean. Traditional sea rituals play a central role in community identity, governance, and ecological stewardship. **Challenges** Modernization and external influences have led to declining adherence to customary marine management practices. Overfishing and habitat degradation threaten marine biodiversity and cultural continuity. **Action** Communities integrate sacred sea rituals with marine conservation efforts, reinforcing traditional taboos (Tambu areas) where fishing is restricted. Customary marine tenure (CMT) practices combine Indigenous ecological knowledge with modern conservation strategies to protect marine species and sustain fisheries. Partnerships with NGOs and local governments support revitalization of rituals.

Source: Prepared by the writing team.

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Chapter 4
Ocean hazards of natural origin

Key points

- A methodological approach that integrates ocean hazards of natural origin into the One Health concept is proposed (see figure I).
- Identifying pathways is essential for assessing the impact of ocean hazards of natural origin on natural and human environments across oceanic scales and for enhancing ocean and coastal resilience.
- Pathways linking "pressures", "ocean hazards" and "impacts-disasters" serve to illustrate the distinctions within ocean hazards of natural origin (see figure XVI).
- Pathways connecting "impacts-disasters" and "mitigation-management-adaptation" serve to highlight available strategies in a multi-hazard context (see figure XVII).

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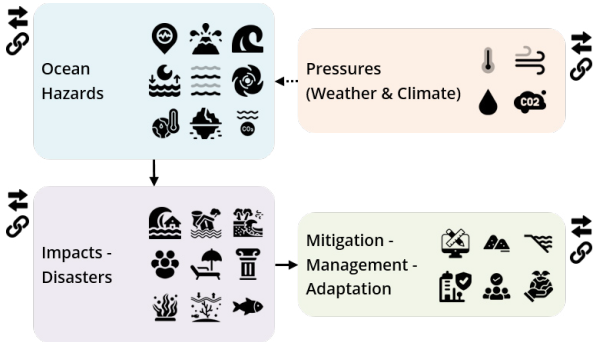
1. Introduction

Ocean hazards of natural origin can be classified into four categories: (a) geophysical or geological; (b) ocean weather, hydrology and climate; (c) ecological; and (d) biological (Pinardi and others, 2024). The present chapter is focused on categories (a), (b) and, partly, (c) (for acidification and deoxygenation, since those hazards largely affect those under categories (c) and (d)). Aspects regarding (c) and (d) are also addressed in other chapters (see sect. 4, chaps. 4–6; and subsect. 5B, chaps. 1 and 2; see also table 2).

The present chapter is a new addition to the *World Ocean Assessment*. In the first and second Assessments, elements that were relevant to ocean hazards or that integrated them within broader environmental and ecological frameworks were addressed; however, in the third *Assessment*, the topic has been elevated to a focused chapter. Accordingly, the approach presented below is intended to serve as a blueprint for future versions of the *Assessment*.

The approach taken is graphically represented by the flow chart contained in figure I.

Figure I
Flow chart of the approach to the present chapter, including its four core components



Source: Prepared by the writing team.

Note: Arrows denote the pathways between core components; "pressures" make part of the pathways only for hazards affected by weather and climate, hence the dotted line; double arrows denote information exchanges and link icons refer to other chapters of the third *World Ocean Assessment* as presented in table 2).

Its aim is to highlight "pathways" that connect the four core components, with the goal of facilitating a structured overall assessment of ocean hazards of natural origin within the framework of the third *World Ocean Assessment*. The approach is aligned with the nationally determined contributions and dialogues under the United Nations Framework Convention on Climate Change (UNFCCC) in relation to the role of ocean hazards of natural origin in the above context and to the road map towards ocean/coastal resilience (UNFCCC, 2023, 2024a, 2024b).

Table 1
Extended literature by chapter part

Sub-Section	Extended Literature
5B4.3.1	Doocy and others (2013), Espinosa and others (2017)
5B4.3.2	Daniel (2014), Jaiswal and Wald (2013), Skufina and others (2019)
5B4.3.3	-
5B4.3.4	-
5B4.3.5	Nawarat and others (2024)
5B4.3.6	Wang and Lin (2020), Earl-Spurr and others (2023), Lamers and others (2023), Heidarzadeh and Rabinovich (2021), Kim and Omira (2024), Raible and others (2021), Gaertner and others (2018), Hoque and others (2017), Catto (2016), Leroux and others (2018), Heming and others (2019), Wang and others (2016), Catto and others (2019), Knutson and others (2019), Hart (2003)
5B4.3.7	Dusek and others (2019), Vilibic and others (2016), Huang and others (2022), Angove and others (2021)
5B4.3.8	-
5B4.3.9	Xu and Perrie (2012), Wong and others (2019), Dissanayake and others (2021), Hemer and others (2010, 2013), Meucci and others (2023), Shimura and other (2015), Young and others (2011), Hsu and others (2023), Lee and others (2022)
5B4.3.10	-
5B4.3.11	Harris and others (2018)
5B4.3.12	Zemp and others (2020), Sraneo and Heimbach (2023), Khan and others (2022), Zhou and others (2021), Cape and others (2019), Sejr and others (2022)
5B4.3.13	Wood and others (2024), Yuan and others (2024), Couasnon and others (2020), Wang and others (2021), Howley and others (2018), Cardoso and others (2008), Shore and others (2021), Draut and others (2009), Milner and others (2018), Dankers and others (2014), Eccles and others (2019)
5B4.3.14	Fakhruddin and Eslamian (2017), Thomsen and Green (2019), Lake (2011), Ravindra and others (2010), Oh and others (2023), Dai (2011, 2013)
5B4.3.15	Chong and others (2014), Hu and others (2024), Bui and others (2024), Vu and others (2024), Datta and others (2009), Ferguson and Gleeson (2012)
5B4.3.16	-
5B4.3.17	Levin (2003), Sperling and others (2016), Orio and others (2021)
5B4.4.1	-
5B4.4.2	Lewis and others (2023), Angove and others (2021), Lamers and others (2023)
5B4.4.3	Huss and others (2021), Xie and others (2023)
5B4.4.4	Vousdoukas and others (2018, 2020), Dedekorkut-Howes and others (2020), Casella and others (2014), Polk and Eulie (2018)
5B4.4.5	
5B4.4.6	Dankers and others (2014), Barbier and others (2011), Howley and others (2018), Mansour Abdelkareem (2024), Ward and others (2018), Wahl and others (2015)
5B4.4.7	Hingst and others (2024), Bhattachan and others (2018), Chang and others (2019), Hu and others (2024), Murgulet and Tick (2008), Miyan (2015), Ravindra and others (2010), Osemwegie and Boko-Koiadia (2019)
5B4.4.8	-

Source: Prepared by the writing team.

Table 2
Links to other sections and chapters of the third *World Ocean Assessment*

		Links to WOA III Chapters/Sections					
Pressures	Ocean temperature	S4.C1	S4.C2	S4.C3			
	Air temperature	S4.C1	S4.C2	S4.C3			
	Wind	S4.C1	S4.C2	S4.C3			
	Precipitation	S4.C1	S4.C2	S4.C3			
	CO2	S4.C1	S4.C2	S4.C3			
Ocean Hazards	Tsunamis		S4.C3				
	Earthquakes		S4.C3				
	Volc. Eruptions		S4.C3				
	Subsidence		S4.C3				
	Coastal Erosion	S4.C1	S4.C3				
	Cyclones / Meteotsunamis	S4.C1	S4.C3				
	Sea-level rise	S4.C1	S4.C3				
	Waves /	S4.C1	S4.C3				
	Storm Surge /	S4.C1	S4.C3				
	Marine heatwaves	S4.C1	S4.C3				
	Glacial melt	S4.C1	S4.C3				
	Heavy rainfall /	S4.C1	S4.C3				
	Droughts	S4.C1	S4.C3				
	Saltwater intrusion	S4.C1	S4.C3				
	Acidification / Deoxygenation	S4.C1	S4.C3				
Impacts -Disasters	Loss of land	S4.C1	S4.C3	S5A.C9			
	Loss of life	S4.C1	S4.C3	S5B.C2			
	Infrastructure damage	S4.C1	S4.C3	S5A.C3	S5A.C9		
	Property damage	S4.C1	S4.C3	S5A.C9			
	Livelihood disruption	S4.C1	S4.C3	S5A.C3	S5B.C3		
	Navig./Shipp. challenges	S4.C1	S4.C3	S5A.C6	S5A.C9		
	Tourism disruption	S4.C1	S4.C3	S5A.C2	S5A.C4	S5A.C9	S5B.C3
	Cultural heritage Loss/Destruction	S4.C1	S4.C3	S5A.C7	S5A.C9		
	Habitat Loss/Destruction	S4.C1	S4.C3	S4.C5	S5A.C9	S5B.C1	S5B.C2
	Biodiversity Loss/Disruption	S4.C1	S4.C3	S4.C4	S5A.C5	S5B.C1	S5B.C2
	Saltwater intrusion	S4.C1	S4.C3				
	Water quality issues	S4.C1	S4.C3	S5A.C8	S5B.C2		
	Food systems disruption	S4.C1	S4.C3	S5A.C1	S5A.C5	S5B.C2	
	Coastal Erosion	S4.C1	S4.C3	S5A.C9			
	Coastal Flooding	S4.C1	S4.C3	S5A.C9			
Mitigation-Management-Adaptation	Monitoring, Forecasting and Early Warning Systems						
	Warning Dissemination & Communication						
	Preparedness & Response						
	Sectoral medium to long term planning						
	Nature-Based Solutions						
	Digital Twins						
	Managed Retreat						
	Infrastructure Upgrading / Climate-proofing / Building Codes	S4.C2	S5A.C*	S5B.C*			
	Marine and Maritime Spatial Planning						
	Governance Framework						
	Disaster Recovery Planning						
	Equitable Coastal Resilience						
	Government Investments, Financing & Insurance						
	Capacity Building						
	Corporate Social Responsibility						

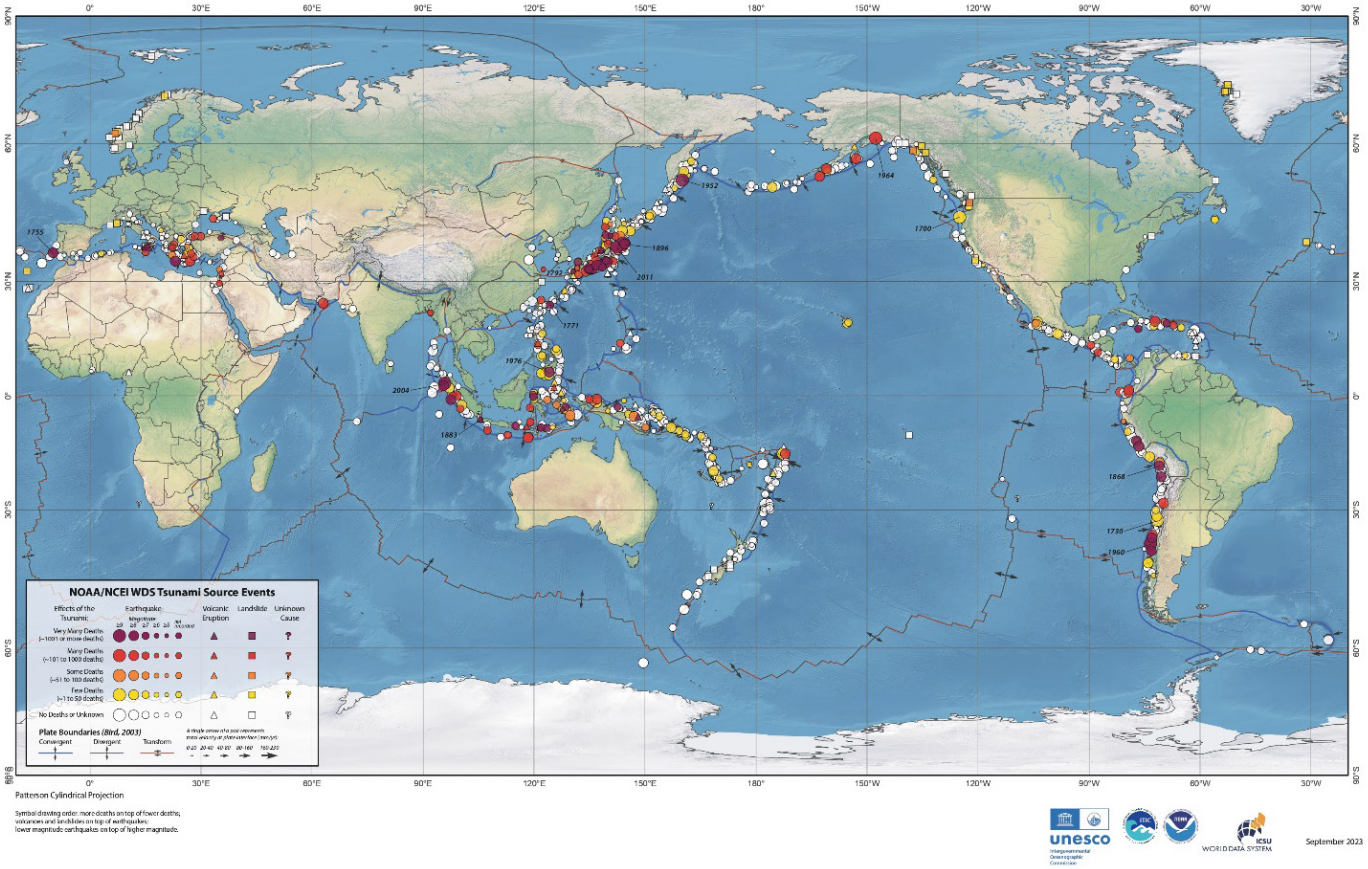
* Potential link to all Chapters of this Section

Source: Prepared by the writing team.

2. Ocean hazard analysis

The present part of the chapter contains an analysis of ocean hazards of natural origin within the context of identifying pathways that connect the "pressures", "ocean hazards" and "impacts-disasters" components (see figure I). It is divided into 17 sub-parts, each containing a description of a distinct hazard. An analysis is presented in figure XVI. Information in figure XVI reflects the assimilation of available knowledge regarding the examined hazards in the relevant literature (see table 1). Figure XVI should not be interpreted beyond its intended use, considering the uncertainties arising from such large-scale assessments when studying phenomena with significant local and regional variations. In that light, the present chapter is fundamentally linked to section 4, chapters 1 to 3, of the third *World Ocean Assessment*, with detailed links identified in table 2.

Figure II
Known tsunami sources from 1610 B.C.E. to 2023 C.E.



Source: Intergovernmental Oceanographic Commission, 2019.

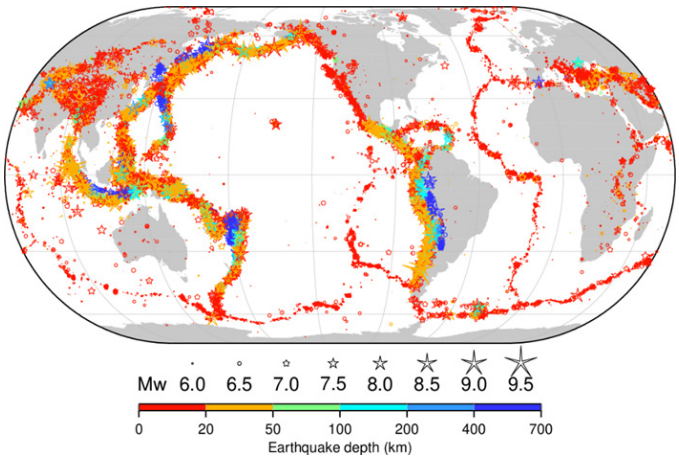
Tsunamis

Geohazards can have major impacts on the human and natural environment, ranging from direct impacts (loss of life and damage to infrastructure and property), to indirect impacts (economic loss, social disruption and environmental degradation). Tsunamis are long sea waves with wave periods typically within the minutes to hour range. Their wavelengths are in the order of tens to hundreds of kilometres depending on the dimensions of their causes (Levin and Nosov, 2016). Although tsunamis can be produced by several mechanisms (Bryant, 2008), submarine geological processes produce the majority of these waves. Shallow submarine earthquakes with moment magnitude greater than 6.5 produce 79% of the global number of tsunamis, while submarine volcanic eruptions or landslides produce 18%. Most tsunamis, including the largest, are generated along subduction zones (see figure II). Tsunamis caused an estimated 250,000 deaths and $280 billion in economic losses between 1998 and 2017 (United Nations Office for Disaster Risk Reduction (UNDRR), 2018).

Earthquakes

Global seismic activity is concentrated mainly along the boundaries of moving lithospheric plates (Lay and Wallace, 1995; see figure III). The sudden rupture of rocks releases stored dynamic energy in the form of seismic waves. Every year, on average, about 15 to 18 earthquakes of magnitude 7 or greater occur globally, and there are hundreds that exceed magnitude 6 (United States Geological Survey (USGS), 2024). Although most tectonic earthquakes occur at shallow depths (focal depth of less than 80 km), seismic activity has been observed at depths of up to about 720 km (the maximum depth of lithospheric subduction). Seismic waves travel from the seismic source in all directions within the Earth's interior, reaching the surface and causing the ground to shake. Earthquakes that occur in association with volcanic activity represent less than 10% of the total number of earthquakes. Earthquakes caused an estimated 500,000 deaths and $380 billion in economic losses between 1998 and 2017 (UNDRR, 2018; Wallemacq and Rowena, 2018).

Figure III
Epicentres of earthquakes



Source: International Seismological Centre (ISC), 2024.

Volcanic eruptions

The geographical distribution of active volcanoes worldwide is similar to that of earthquake sources (Loughlin and others, 2017; see figure IV). More than 75% of all active volcanoes are located along submarine and coastal volcanic belts, such as the Ring of Fire in the Pacific Ocean. Strong volcanic eruptions that occur near populated areas become dangerous or even destructive. Over the past 500 years, volcanic eruptions are estimated to have caused more than 200,000 deaths (Muzeau and others, 2010), with roughly half of those occurring during the period from 1900 to 2009 (Doocy and others, 2013b).

Tectonic subsidence

In regions characterized by subduction zones, the overriding lithospheric plate may experience subsidence. As the subducting plate pulls down the Earth's crust, large areas can gradually sink. This is a large-scale geodynamic process that is driven by plate tectonics mechanisms (Turcotte and Schubert, 2002). Tectonic subsidence may also occur suddenly in the overriding plate during a large subduction zone earthquake. Therefore, during large earthquakes, fault rupture can cause abrupt subsidence, thereby triggering tsunamis or permanently lowering parts of the coastline. Furthermore, in regions near convergent boundaries, heavy sediment deposition from rivers or glaciers can cause the crust to bend and subside due to weight (often seen in coastal or delta regions). Tectonic subsidence in coastal regions lowers the land relative to sea level, making those areas more vulnerable to flooding, storm surges and sea-level rise. Gradual subsidence over time can cause damage to infrastructure, especially in areas where the land is subsiding unevenly. The opposite process, tectonic uplift, can also cause similar damage to infrastructure and lead to changes or disruptions in navigable waterways.

Coastal erosion

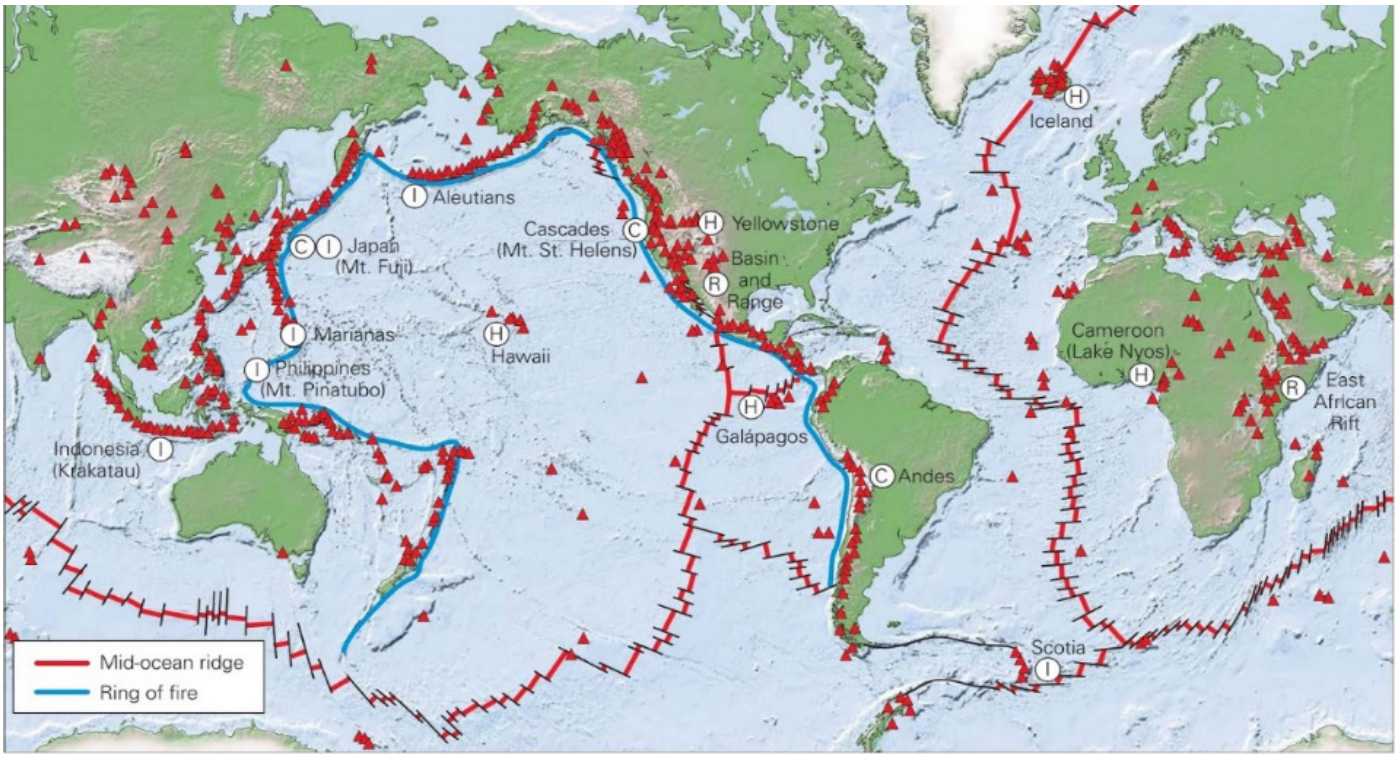
Through a global assessment of shoreline typology using satellite imagery (Hulskamp and others, 2023), 26%, 12%, 27% and 33% of ice-free shorelines were classified as sandy, muddy, rocky and vegetated, respectively, using automated image detection validated at over 50 sites. Luijendijk and others (2018) provide historical sandy shoreline position change rates during the period from 1984 to 2016, showing that 24% of sandy coasts had eroded, 28% had accreted and 48% had remained stable.

It has been stated with high confidence (Intergovernmental Panel on Climate Change (IPCC), 2021) that sandy shorelines will retreat in most regions of the world in the absence of additional sediment sources or physical barriers to shoreline retreat (for erosion trends for high-latitude permafrost-built shorelines, see sect. 4, subchap. 5K). The total length of sandy shorelines around the world projected to retreat by more than 100 m by the end of the century is about 35% greater under Representative Concentration Pathway (RCP) 8.5 (about 130,000 km) compared with that under RCP 4.5 (about 95,000 km). Vousdoukas and others (2020) find that 13.6–15.2% (36,097 km–40,511 km) of the world's sandy coastline could face shoreline retreat of more than 100 m by 2050, increasing to 35.7–49.5% (95,061 km–131,745 km) by the

end of the century. Concentrating on the densely populated low-elevation coastal zone of the world, comprising 31% of the world's sandy coastline, Vousdoukas and others (2020) show that about one third of the global low-elevation coastal zone will experience shoreline retreat of more than 100 m by 2050, an estimate that reaches 52% and 63% by the end of the century, under RCP 4.5 and RCP 8.5, respectively (see figure V).

Figure IV

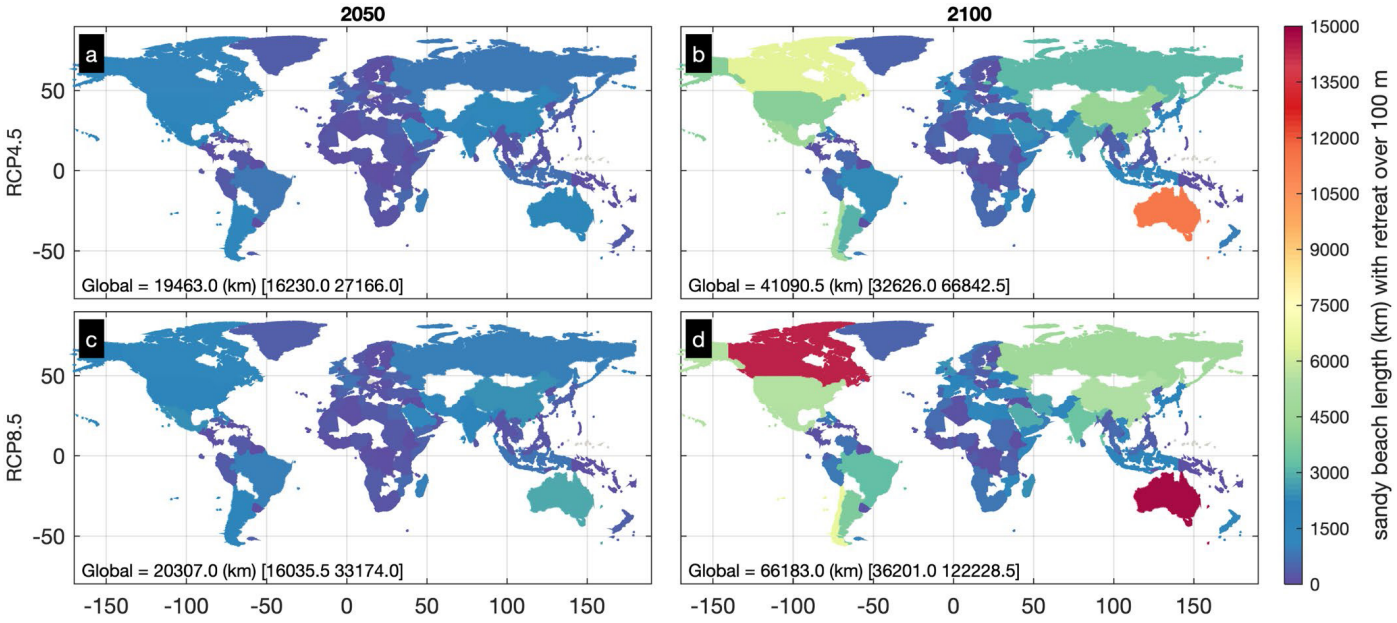
Main lithospheric plates and distribution of volcanoes



Source: Learning Geology, 2024.

Figure V

Projected retreat of sandy shorelines



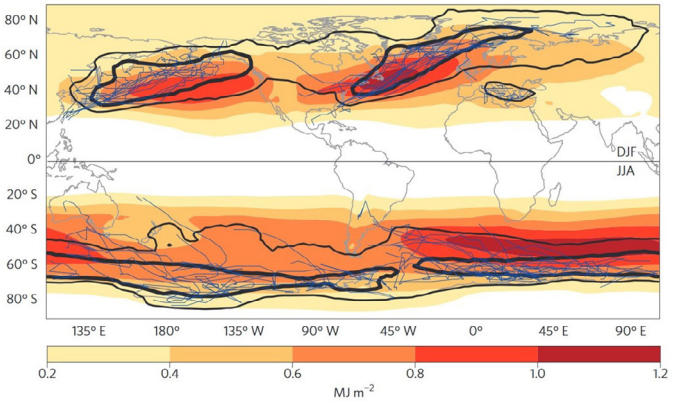
Source: Vousdoukas and others, 2020.

Note: Length of sandy-beach coastline projected to retreat by more than 100 m by 2050 (a, c) and 2100 (b, d), under RCP 4.5 (a, b) and RCP 8.5 (c, d), by country.

Tropical and extratropical cyclones

Cyclogenesis occurs through different mechanisms at varying latitudes (Emanuel, 1991) and plays a crucial role in global circulation by transporting heat and moisture. Cyclogenesis is a significant hazard for coastal areas and maritime activities, especially in the form of tropical cyclones, which are warm-core, axisymmetric vortices with radii of between 100 km and 1,000 km, fuelled by thermodynamic disequilibrium between the atmosphere and ocean surface. Tropical cyclones are known as hurricanes or typhoons, depending on the region. These terms also refer to specific classifications of tropical cyclones that exceed certain wind speed thresholds in different regions. Annually, around 90 tropical cyclones occur globally (Emanuel and others, 2023) and cause severe impacts in coastal regions through strong winds, intense rainfall and storm surge effects. Extreme events can lead to hundreds of thousands of casualties (Cerveny and others, 2017). Since the 1970s, increased coastal exposure and climate change have exacerbated damage and the number of affected individuals (Kunze, 2021). At higher latitudes, extratropical cyclones, such as polar lows and Mediterranean hurricanes (Medicanes or tropical-like cyclones) (see Miglietta and Rotunno, 2019), which are smaller and shorter-lived than tropical cyclones, are influenced by sea-surface heat fluxes and baroclinic instability and significantly affect annual precipitation in coastal areas (Schultz and others, 2019).

Figure VI
Wintertime extratropical storm eddy kinetic energy and track density



Source: Shaw and others, 2016.

Note: Wintertime (adapted for northern and southern hemispheres) extratropical storm eddy kinetic energy (colour) and track density (contours). Thick/thin contours: 20/10 tracks (10^6 km^{-2}) per season; blue lines: individual tracks for the top 0.5% most intense cyclones.

Accurate tracking and property assessment of cyclones are vital for disaster management and long-term preparedness. However, challenges remain in identifying long-term trends due to limited observational records and inter-annual variability. Although studies indicate potential increases in tropical and tropical-like cyclone intensity due to warming, projections regarding frequency changes and poleward migration of maximum intensity remain uncertain (Knutson and others, 2020). In addition, sea-level rise may heighten storm impacts even if storminess decreases (Lionello and others, 2017).

Meteotsunamis

Meteotsunamis are long barotropic ocean waves generated by the resonance between atmospheric perturbations and sea surface oscillations. This resonance can occur when the propagation velocities of these atmospheric disturbances and sea waves align, in the ocean (Proudman resonance) or along coastlines (Greenspan resonance), or through interactions between incoming waves and the oscillation characteristics of a harbour or bay. Nearshore processes, such as topographic amplification or focusing, can further enhance such waves (Ličer and others, 2017). Depending on the mechanisms involved, meteotsunamis may manifest as solitary waves that impact coastlines or as seiches that oscillate in bays, with amplification reaching up to 100 times the "inverse barometer" response to the atmospheric disturbance (Pattiaratchi and Wijeratne, 2015).

While the triggering conditions for meteotsunamis occur at large scales, significant events arise only when multiple conditions coincide (Monserrat and others, 2006). Consequently, meteotsunamis often exhibit local characteristics, with hotspots where such events frequently occur (e.g. the Mediterranean Sea, the East China Sea, the East Coast of the United States of America and the Great Lakes in North America; Rabinovich, 2020). Severe meteotsunami events can cause considerable economic losses and affect local economies (see, e.g., Šepic and others, 2016), and possibly lead to fatalities.

Characterizing meteotsunami hazards is challenging in terms of both short-term early warning planning and long-term climate-proof coastal planning. Early warning systems use approaches such as synoptic indices that correlate atmospheric patterns with meteotsunamis, high-resolution numerical modelling of relevant physical processes and probabilistic methods (Denamiel and others, 2023). Global adjustments in sea-level monitoring protocols to one-minute intervals, which were initiated

following the Indian Ocean tsunami that occurred in 2004, have improved meteotsunami detection and long-term climatological trend reconstruction. Advances in technologies, such as high-frequency radars and global navigation satellite system sensors, have also enhanced tsunami monitoring in the ionosphere (Angove and others, 2021).

Figure VII
Locations of meteotsunami occurrences

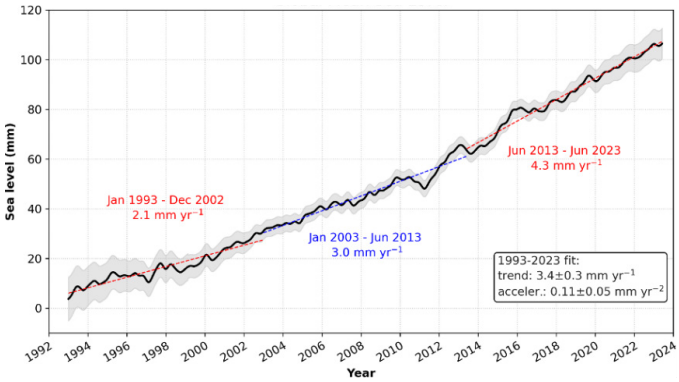


Source: Pattiaratchi and Wijeratne, 2015.

Sea-level rise

It is well established that the ice loss from the Greenland and Antarctic ice sheets, glacier mass loss and the expansion of ocean volume from ocean warming (Cazenave and Moreira, 2022) cause global sea level to rise, and human influence has very likely been the main driver of such increases since at least 1971 (IPCC, 2021). It is also well established that the rate of global sea-level rise is increasing (von Schuckmann and others, 2024; World Meteorological Organization (WMO), 2024), with a very likely acceleration rate of 0.094 mm/yr^2 (0.082–0.115) for the period from 1993 to 2018 (IPCC, 2021). At the regional scale, sea-level rise is not uniform. While most areas show a positive trend, localized regions with negative trends can also be observed (Fasullo and Nerem, 2018). It is well established that, in the past 30 years, nearly 50% of the ocean has experienced sea-level rise at rates exceeding the global average, particularly in regions influenced by major western boundary currents, as well as parts of the western Pacific, the Indian Ocean and some areas of the Atlantic Ocean (von Schuckmann and others, 2024). Although at the regional scale sea-level trends are still dominated by steric changes (Stammer and others, 2013), studies show that accelerated land ice melt will lead to associated fingerprints becoming detectable (Tamisiea, 2011; Coulson and others, 2022; IPCC, 2019). Sea-level rise has increased the adverse effects of coastal floods (well established), storms and tropical cyclones (established but incomplete), and hence the consequent losses and damages, the increasing vulnerability of inhabitants and infrastructure and food security risk, in particular in low-lying areas and island States (IPCC, 2022). Adaptation and mitigation measures, such as the restoration of mangroves and coastal wetlands, reduce the risks from sea-level rise (IPCC, 2022).

Figure VIII
Global mean sea-level rise



Source: von Schuckmann and others, 2024.

Note: Global mean sea-level time series from January 1993 to June 2023 (curve) and its uncertainty envelope (shaded).

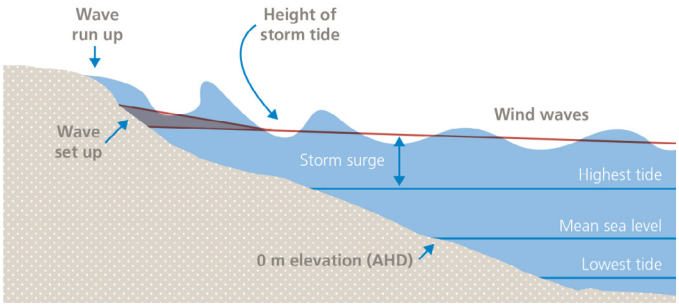
Waves and wave run-up

Wave run-up is a combination of wave set-up and shoreline oscillation (swash) from each incoming wave (see figure IX). It includes contributions from sea, swell and infragravity waves, varying over seconds to minutes. On gently sloping beaches, infragravity wave run-up can dominate. During storms, wave run-up on open coast beaches may reach 3 to 6 m above other components (Hughes, 2016). Run-up characteristics change depending on beach and offshore wave properties (Holman, 1986) and are the main drivers of beach-face hydrodynamics and morphodynamics (Elfrink and Baldock, 2002). Run-up also plays a critical role in dune erosion during storm conditions (Ruggiero and others, 2001) and structure overtopping (van der Meer and Stam, 1992). Run-up is therefore key to successful coastal planning and management and a critical parameter in assessing the effect of sea-level rise on coastal inundation.

Wave run-up is closely related to many of the hazards presented in the present part of the chapter (tsunamis, tropical and extratropical cyclones, meteotsunamis, sea-level rise, and storm surge and coastal flooding).

Accordingly, it is difficult to disengage its assessment from a multi-hazard approach when it comes to the flow chart contained in figure I, especially considering that, with the exception of tsunamis, all other related hazards will be exacerbated by climate change. There are several studies highlighting regional variability in wave climate under present and future conditions. Nevertheless, regardless of regional variability, there appears to be consensus that major impacts will derive from significant increases in wave heights, changes in the frequency of occurrence and magnitude of extremes, and changes in wave directionality (Casas-Prat and others, 2024; Lobeto and others, 2021).

Figure IX
Schematic representation of the surf zone



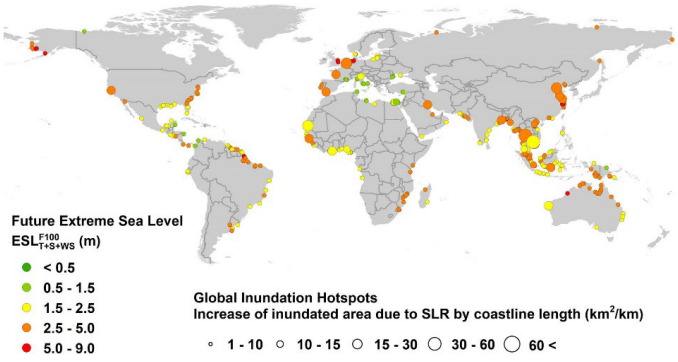
Source: Department of Sustainability and Environment (DSE), 2012.

Storm surge and coastal flooding

Coastal flooding is the episodic or permanent flooding of low-elevation coastal zone due to extreme total water levels. Extreme total water levels are composed of relative sea-level rise, which combines sea-level rise and local subsidence, storm (wind and pressure-driven) surge, tides and wave set-up (Rueda and others, 2017). In many cases, storm surge is the dominant contributor to extreme total water level. Hazards associated with coastal flooding are highly likely to increase in the coming decades for the majority of the world's coastlines (IPCC, 2021). Vousdoukas and others (2018) project a global increase by 2100 of 34 to 76 cm of the 100-year return period extreme total water level under the RCP 4.5 scenario, and an increase of 58 to 172 cm under the RCP 8.5 scenario. Moreover, after 2050, the present-day high return period extreme total water levels are expected to become much more frequent in the majority of the world's coastal areas, especially in the tropics (Vitousek and others, 2017), even under the most optimistic 1.5°C warming scenarios (Tebaldi and others, 2021).

Looking at coastal flooding impacts on a global scale, without taking coastal protection and adaptation into account, an estimated area of 533*10³km² (512–603), a total of 148*10⁶ (128*10⁶–171*10⁶) people and assets valued at 7,761*10⁹$ (6,466–9,135) would be at risk under a present day 100-year return period extreme total water level event, increasing by 2100 by 33%, 36% and 32% under the RCP 4.5 scenario, respectively, and by 48%, 52% and 46% under the RCP 8.5 scenario, respectively (Kirezci and others, 2020). Within the above context, impacts on food systems (especially fisheries and aquaculture) should not be overlooked (Sühring and others, 2023). Looking at risk, Tiggeloven and others (2020) found a 150-fold increase in expected annual damage by 2100 under the RCP 4.5-Shared Socioeconomic Pathway 2 scenario if no adaptation to coastal flooding occurs. When applying different adaptation scenarios, the increase reduces to 11- to 39-fold, depending on the adaptation pathway selected.

Figure X
Global hotspot regions of changes in episodic coastal flooding in 2100 under Representative Concentration Pathway 8.5 (difference between projected episodic flooding in 2100 minus present-day episodic flooding)



Source: Kirezci and others, 2020.

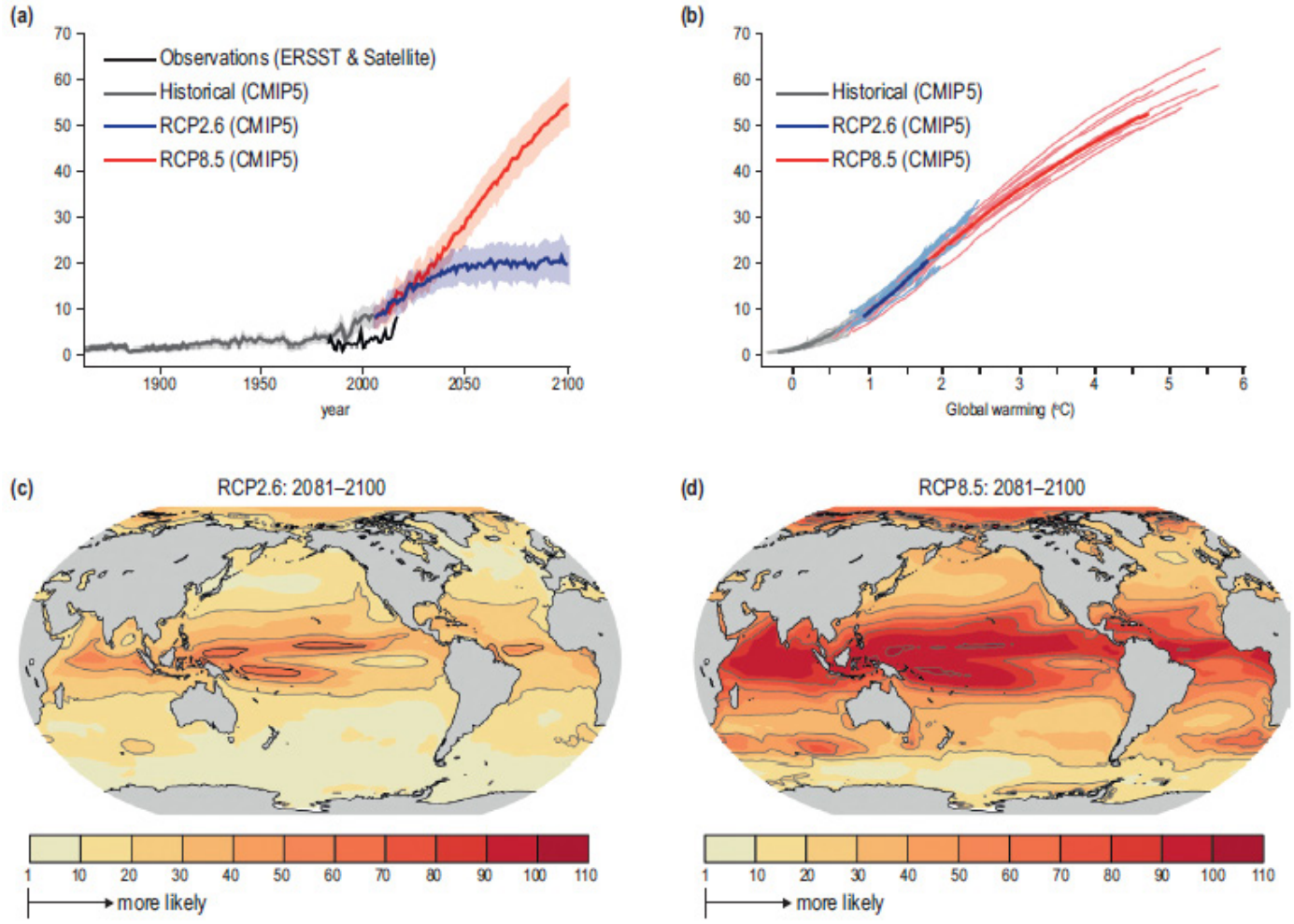
Marine heatwaves

A marine heatwave is a period of at least five consecutive days of sea-surface temperatures above the 90th climatological percentile (Hobday and others, 2016). Marine heatwave result from air-sea interactions, shifts in ocean currents and climate variability such as El Niño (IPCC, 2019). It is well established that, since the 1980s, marine heatwave frequency has doubled, with further increases expected, especially in tropical and Arctic waters, and human influence has very likely contributed to most of them since at least 2006 (IPCC, 2019, 2021). With further increases in intensity and frequency observed, and

projected in the coming decades, marine heatwaves are emerging as pervasive stressors for marine ecosystems globally (Smith and others, 2023; see figure XI), thereby exposing species and ecosystems to environmental conditions beyond their tolerance and acclimation limits (IPCC, 2022). Adverse impacts already reported include the reduction of primary production, the migration or reduction of endemic species, the emergence of species from other regions and mass mortality of organisms (Smith and others, 2023; Oliver and others, 2019; Garrabou and others, 2022). Those changes can, in turn, have adverse impacts on human systems, including on fisheries and aquaculture (Cheung and Frölicher, 2020; IPCC, 2022; Wakelin and others, 2021).

Figure XI

Global and regional changes in the probability ratio of marine heatwaves



Source: IPCC, 2019.

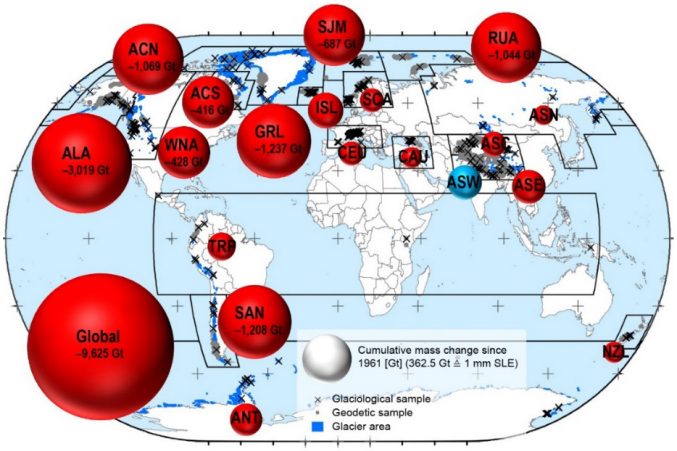
Note: The probability ratio is the fraction by which the number of marine heatwave days per year has changed since 1850–1900. (a): changes in the annual mean probability ratio of marine heatwaves exceeding the 99th percentile of pre-industrial local daily sea-surface temperature averaged over the ocean. (b): same as (a), but the probability ratio is plotted for different levels of global surface atmospheric warming and for the individual models. The simulated time series in (b) are smoothed with a 10-year running mean. (c) and (d): simulated regional changes in the multi-model mean probability ratio of marine heatwaves exceeding the pre-industrial 99th percentile in 2081–2100 for the RCP 2.6 scenario (c) and the RCP 8.5 scenario (d).

Glacial melt

Glacial melt refers to the large-scale melting of glaciers and ice sheets, which releases vast amounts of freshwater into the world's oceans. Glacial melt contributes to sea-level rise, while the influx of freshwater disrupts ocean salinity and density, thereby also modifying habitat conditions, nutrient availability and the biological productivity of affected regions (IPCC, 2019). Ice loss from glaciers and ice caps accounts for about 60% of the ice

loss that contributes to sea-level rise, with the remaining attributed to the melting of the Antarctic and Greenland ice sheets (Meier and others, 2007; see figure XII). As a result, sea-level rise has reached approximately 1.48 ± 0.26 mm per year from all ice-covered regions (Jacob and others, 2012). According to projections, glacier melt could contribute an additional 10 to 25 mm to sea-level rise by 2100 (Meier and others, 2007), while the Greenland ice sheet alone could contribute between 75 and 140 mm to sea-level rise over the same period (Gillet-Chaulet and others, 2012). Freshwater input from glacial melt affects regional dynamics and global overturning circulation (Cenedese and Straneo, 2023), while also affecting nutrient and carbon cycling, thereby influencing primary and secondary productivity in marine ecosystems (Oliver and others, 2020). This affects not only coastal areas, but also the freshwater discharged downstream through glacial-fed rivers (Hock, 2014).

Figure XII
Regional share of glaciers in sea-level rise from 1961/62 to 2015/16



Source: World Glacier Monitoring Service, 2024; adjusted from Zemp and others, 2019.

Heavy rainfall and river flooding

Heavy rainfall in watersheds and associated river flooding can pose significant threats for downstream coasts, through compound flooding, degraded water quality, saltwater intrusion and threats to marine ecosystems. Compound flooding is the simultaneous occurrence of multiple flood drivers, including storm surges, river overflow and torrential rain. Such flooding is particularly severe and can exacerbate the impacts on coastal areas by increasing flooding extents and flow depths (Wright and others, 2019; Shen and others, 2019). Effects typically extend to saltwater intrusion, which contaminates drinking water supplies and affects water quality for years (Marques and others, 2020), leading to direct or indirect health risks for coastal communities. River and compound flooding also affect coastal ecosystems and habitats, through nutrient or sediment transport, physical or biogeochemical changes and habitat disruption (Ge and others, 2021; Furnas, 2011). Climate change is expected to modify the spatial and temporal modulation of rainfall regimes, leading to increased frequency of intense precipitation events and higher flood risks in many regions (IPCC, 2021). This is particularly evident in tropical and subtropical areas, where more intense rainfall is projected to increase flood frequency and magnitude (Winarta and others, 2019). Assessing the impacts of climate change on compound flooding involves significant uncertainties due to the complex interplay of various factors. For example, in Europe, the Mediterranean coasts might currently experience the highest probability of compound flooding; however, according to future projections, there are emerging high probabilities along parts of the northern European coast (Bevacqua and others, 2019).

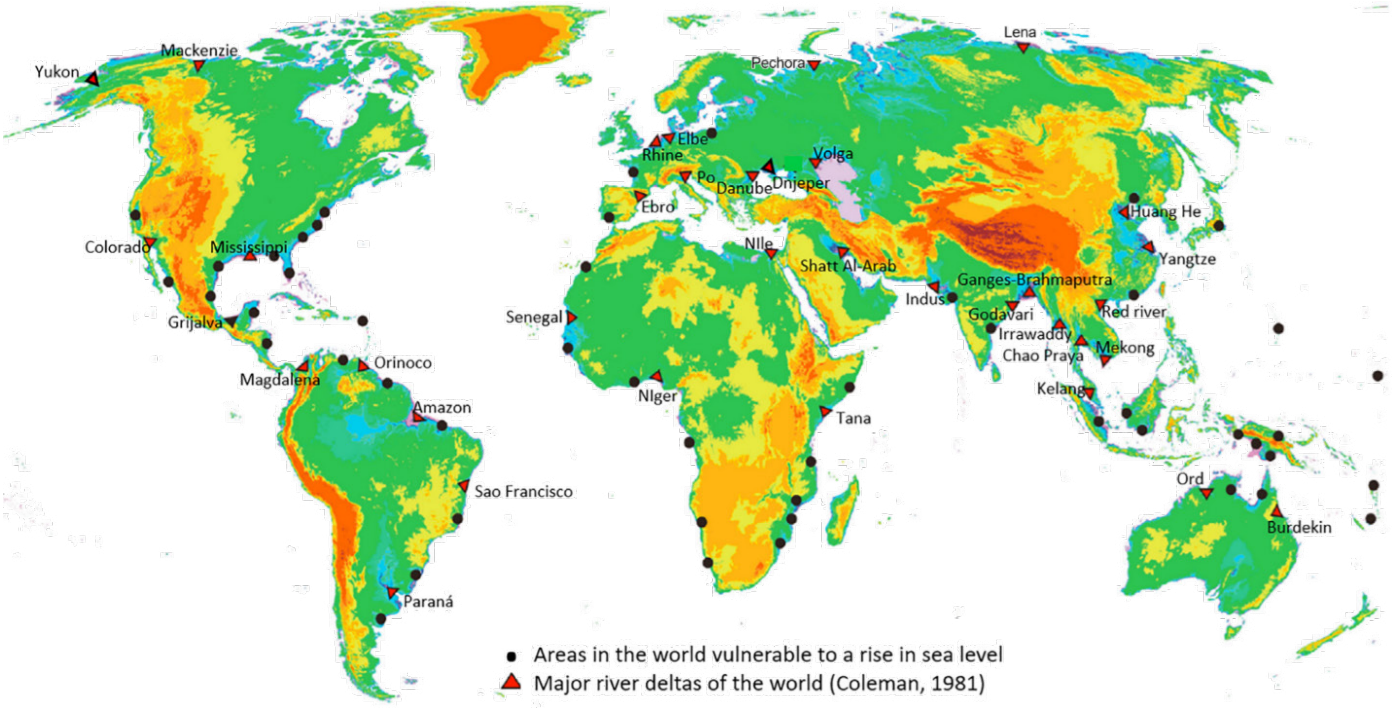
Drought

Although drought is typically considered to be a terrestrial hazard, it can have significant impacts on coastal regions, affecting various aspects of the natural and human environment (Mishra and Singh, 2010). Drought can have an impact on water resources (reduced freshwater availability and salinization of coastal aquifers) (Yihdego, 2017), on ecosystems and biodiversity (Mafi-Gholami and others, 2020) and on human activities (agriculture, industry, energy production, tourism and human health) (Miyan, 2015; Mishra and others, 2015). Droughts occur in both developed and developing countries, with significant impacts on the global ecosystem, varying from region to region. South and South-East Asian countries have been experiencing increasing droughts due to changing precipitation patterns (Miyan, 2015), while the Mediterranean, the Amazon, southern Africa and Central America are projected to be the most affected regions by extreme multivariate drought in the future (Tabari and Willems, 2023; Dai, 2011, 2013). Climate change is expected to exacerbate drought conditions, leading to more frequent and severe droughts (IPCC, 2021), while the combined effects of sea-level rise and coastal flooding and drought will place further stress on coastal regions, leading to increased salinization and reduced groundwater quality (Shishaye, 2021).

Saltwater intrusion

Saltwater intrusion, or the migration of saltwater into freshwater coastal aquifers, has significant environmental impacts on coastal regions (Werner and others, 2013). The increase in water salinity has an immediate impact on drinking water quality and supplies (Moore and Joye, 2021). It also affects crop yields and soil health through biochemical changes in aquifers, which has a detrimental impact on food security in vulnerable regions (Hu and others, 2024; Tully and others, 2019). Saltwater intrusion alters coastal ecosystems, which affects vegetation and wildlife that are dependent on freshwater (Visschers and others, 2022).

Figure XIII
Global hotspots of groundwater vulnerability to saltwater intrusion and sea-level rise



Sources: Modified from van der Gun, 2021; Coleman, 1981.

Saltwater intrusion is a global issue, affecting most coastal aquifers to varying degrees. Areas in China, India and Viet Nam are particularly vulnerable due to their low elevation and high population density, and are thus among the most studied in relevant research. Climate change is expected to enhance saltwater intrusion impacts through increased sea levels, extremes in waves and coastal flooding (Hingst and others, 2024; Werner and Simmons, 2009), while the interplay between multiple hazards (primarily identified at the terrestrial level (e.g. heavy rainfall, river flooding and droughts)) along with human activities (e.g. freshwater pumping) will probably result in unprecedented effects in already problematic coastal areas and elsewhere (Safi and others, 2018).

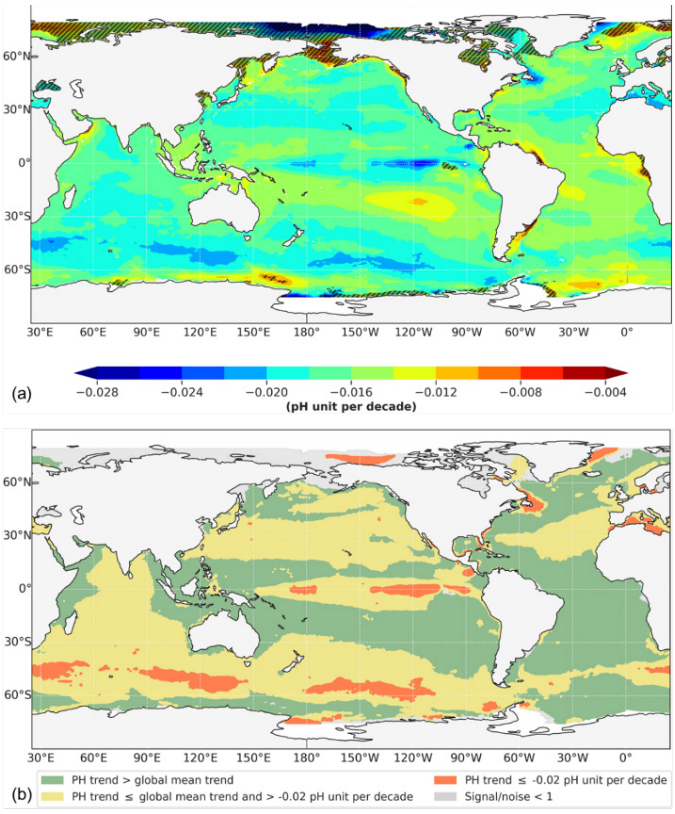
Ocean acidification

The ocean is a major player in the global carbon cycle and an important sink for anthropogenic carbon dioxide (CO_2), helping to moderate climate change (Gruber and others, 2019). It is highly likely that the ocean has absorbed between 20% and 30% of total anthropogenic CO_2 emissions since the 1980s (IPCC, 2019). The decrease of ocean pH is referred to as ocean acidification (IPCC, 2021). Addressing ocean acidification is among the targets of Sustainable Development Goal 14 of the 2030 Agenda for Sustainable Development.

Open-ocean surface pH has declined by a very likely range of 0.017–0.027 pH units per decade since the late

1980s, with the decline in surface ocean pH very likely to have already emerged from background natural variability for more than 95% of the ocean surface area (IPCC, 2019).

Figure XIV
Global ocean surface pH trends



Source: von Schuckmann and others, 2024.

Note: (a): global ocean surface pH trend computed over the period 1985–2022; (b): magnitude of the pH decrease rates.

Ocean acidification has spread deeper in the ocean (Fassbender and others, 2023), surpassing 2,000 m in depth in the northern North Atlantic and in the Southern Ocean (IPCC, 2021). Acidification, in conjunction with other climate change-related environmental stresses, puts at risk many valuable ecosystem services, such as fisheries, aquaculture and shoreline protection (Doney and others, 2020; IPCC, 2022). In addition, together with ocean warming, ocean acidification threatens the future growth of coral reefs (Cornwall and others, 2021) and has diverse adverse impacts on marine biodiversity (IPCC, 2019; Teixidó and others, 2024).

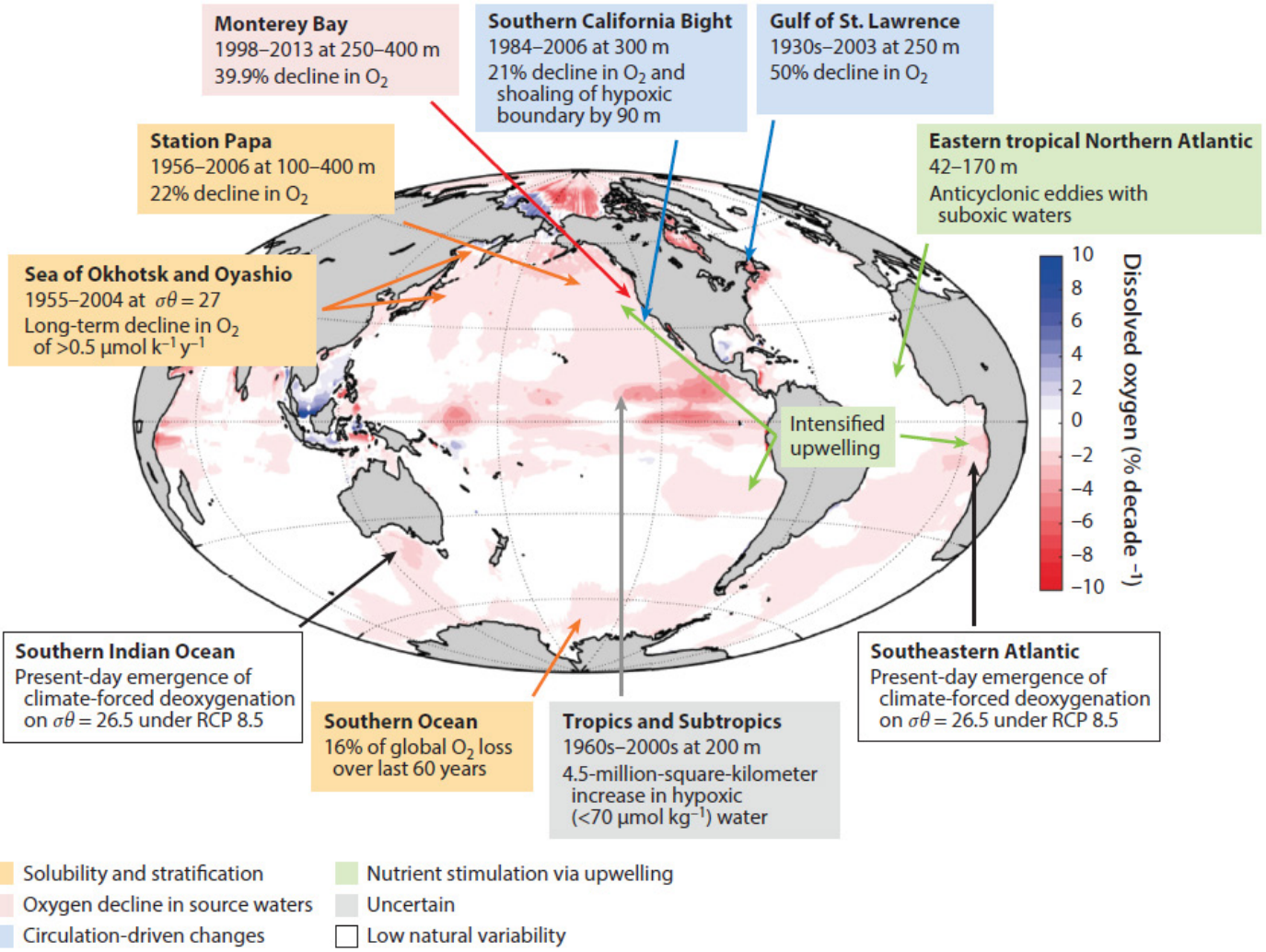
Ocean deoxygenation

It is well established that oxygen loss in the ocean, known as deoxygenation, is a significant consequence of climate change and has been further intensified by other global changes. Over the past 50 to 100 years, deoxygenation has already emerged in most of the global open ocean, which has experienced an average oxygen decline of 2% or more, with even more pronounced losses in intermediate waters (100–600 m) of the North Pacific, East Pacific, tropical regions and the Southern Ocean (Levin, 2018; Oschlies and others, 2018; Breitburg and others, 2018). Natural oxygen variability has made it difficult to detect the emergence of a climate-forced signal of oxygen loss; the observed open-ocean deoxygenation and the expansion of oxygen minimum zones are attributed only in part to human influence (IPCC, 2021).

Continued global ocean deoxygenation is projected to persist under most emissions scenarios, but with regional heterogeneity (IPCC, 2021). Notably, even small changes in oxygenation can have significant biological and biogeochemical effects, including for ocean productivity, nutrient cycling, carbon cycling and marine habitat (IPCC, 2019). Together with warming and acidification, deoxygenation alters ecological communities by increasing the spread of physiologically suboptimal conditions for many marine fish and invertebrates. It is well established that these and other responses have subsequently driven habitat loss, population decline, increased risks of species extirpation, and extinction and rearrangement of marine food webs (IPCC, 2022).

Figure XV

Representative long-term records of open-ocean deoxygenation in intermediate waters superimposed on full ocean percentage change in dissolved oxygen per decade since 1960

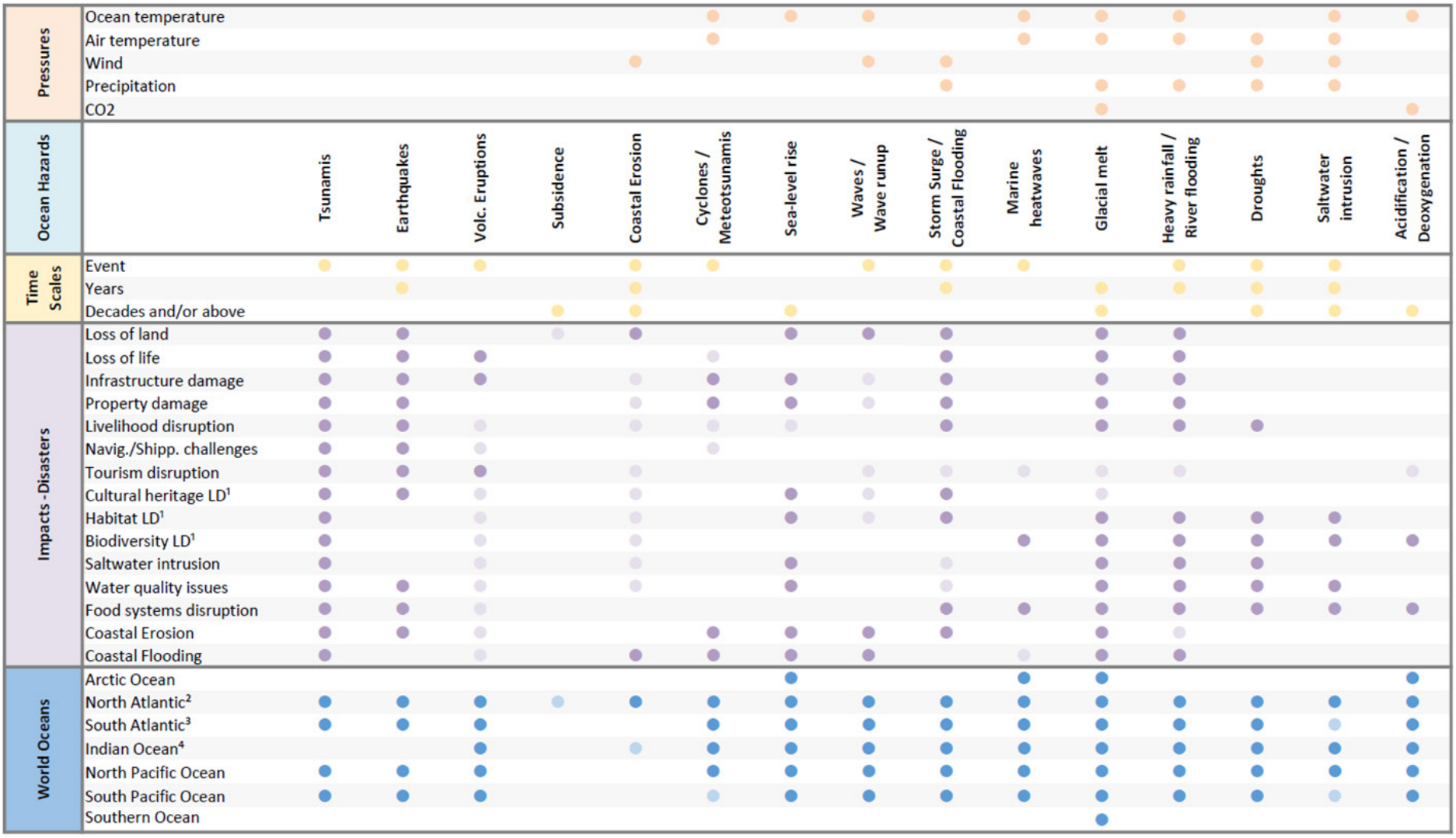


Source: Levin, 2018.

Note: σθ, density surface.

Figure XVI

Pathways connecting the "pressures", "ocean hazards" and "impacts-disasters" components contained in figure I



Source: Prepared by the writing team.

Note: Includes connections with "timescales" and geographical distribution ("world oceans" are listed in accordance with the division under the third *World Ocean Assessment*).

3. Towards ocean and coastal resilience

This part of the chapter analyses strategies towards ocean and coastal resilience that serve this chapter's context of identifying pathways that connect the components "impacts-disasters" and "mitigation-management-adaptation" (see elsewhere in this chapter, particularly figure I), referring to single- and multi-hazard assessment. It is divided into nine sub-parts. Some of the hazards presented below are grouped, as relevant strategies typically address multiple hazards. In the 58 national adaptation plans submitted, the most commonly identified climate hazard was sea-level rise, along with ocean acidification, saltwater intrusion and increased sea surface temperatures (UNFCCC, 2024c). Furthermore, of the Parties that included an ocean-based measure in their national adaptation plans, 12% included reference to human- and climate-induced ocean changes, such as acidification, extreme weather events, sea-level rise, storms and drought (UNFCCC, 2024a).

The "mitigation-management-adaptation" strategies presented in this part of the chapter are closely aligned with evolving international climate policy frameworks on ocean resilience (UNFCCC, 2023, 2024a, 2024b). Ecosystem-based adaptation, enhanced early warning systems and risk-informed planning are prioritized as integral parts of the national adaptation plans that have been developed or are under development (UNFCCC, 2024a, 2024c). Likewise, focus on community engagement and robust governance relates to calls under the United Nations Framework Convention on Climate Change for inclusive, "whole-of-society" approaches to climate resilience.

An analysis of the efforts undertaken under the present part is presented in figure XVII. Information in figure XVII reflects the assimilation of available knowledge regarding the examined strategies in the relevant literature (see also table 1). It is noted that the figure is not focused on specific technical or managerial solutions, but rather serves to divide strategies into the categories "risk reduction" and "governance/institutional/social transformation", in accordance with Pinardi and others (2024). Figure XVII should not be interpreted beyond its intended use, considering the uncertainties arising from such large-scale multi-hazard assessments when studying phenomena with significant local and regional variations, as well as existing knowledge gaps in relevant research. Given the above, this part of the chapter is fundamentally linked to section 4, chapter 2, and to subsections 5A and 5B of the third *World Ocean Assessment*, with detailed links identified in table 2 of this chapter.

Geophysical and geological hazards

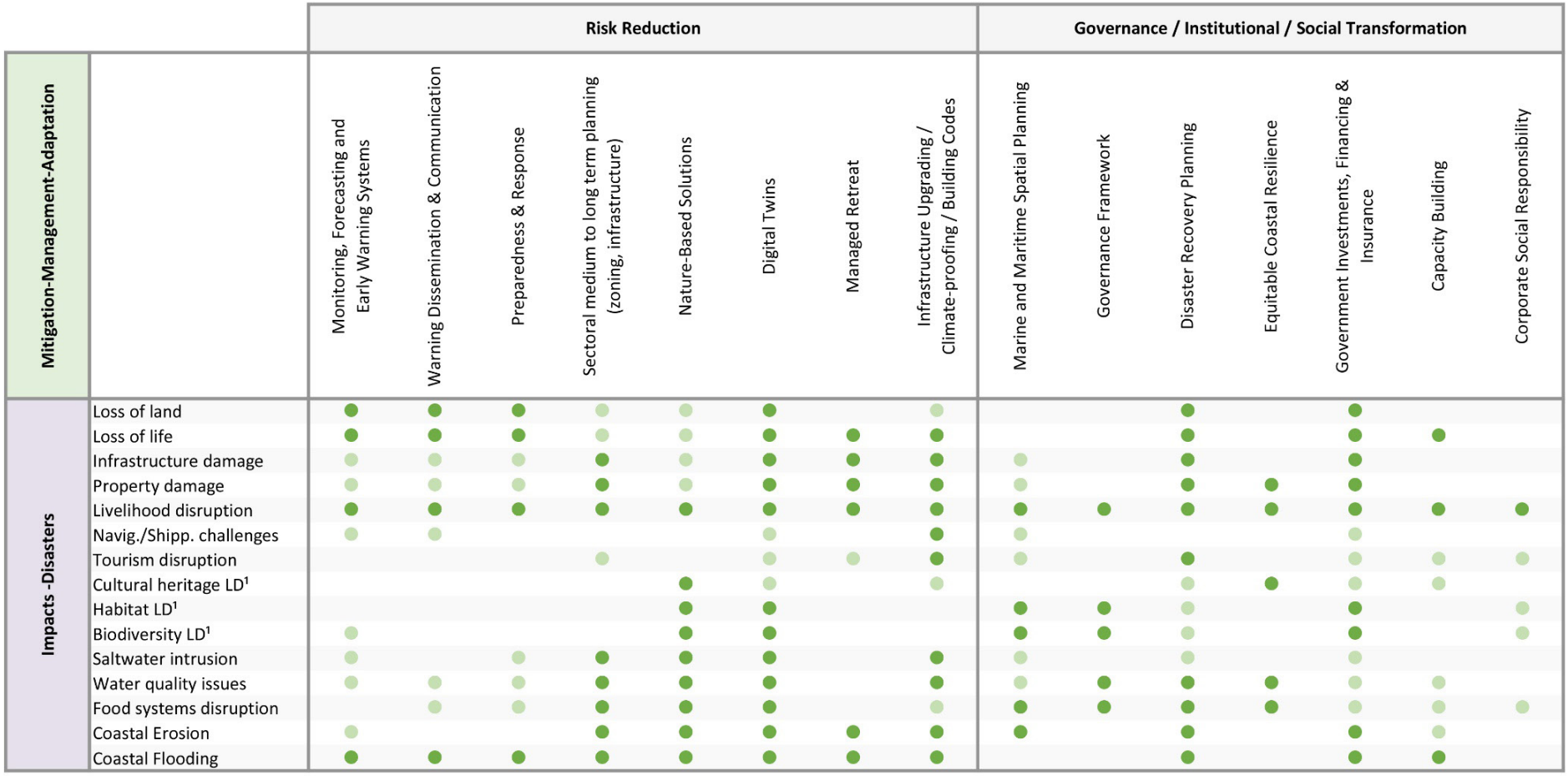
Understanding the impacts of geohazards highlights the need for effective mitigation and adaptation strategies, including preparedness actions, improvement of building codes, development of early warning systems and land-use planning. For instance, after the Tohoku earthquake and tsunami in Japan in 2011, the Government invested heavily in building higher sea walls along the coastline to protect communities and in developing high-tech early warning systems in the country (National Research Institute for Earth Science and Disaster Resilience (NIED), 2024). On a global scale, warning services are provided by regional systems operating in different ocean basins (Intergovernmental Oceanographic Commission (IOC), 2023). These systems focus on end-to-end tsunami warning and mitigation, and are coordinated by IOC of the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a global "system of systems". Communities must be aware and prepared to respond quickly to these extremely short-notice and fast-onset events (IOC, 2022; UNDRR, 2024). Earthquakes can cause extensive damage on land but also liquefaction in coastal zones and partial collapse of structures (e.g. the Loma Prieta earthquake in 1989 and its impact on the San Francisco-Oakland Bay Bridge). Following that earthquake, the public and private sectors made substantial investments in redevelopment and seismic retrofitting programmes to reduce the impact of future earthquakes and enhance earthquake resilience (Zoback, 2014).

Cyclones and meteotsunamis

When meteotsunami risk is recognized and protection is economically justified, for example for strategic infrastructure, design criteria for coastal structures and flood protection systems can be adapted to account for those events (de Jong and others, 2021). Nevertheless, in most cases, early warning remains the backbone of meteotsunami risk reduction, although key obstacles include observational challenges (limited spatial and temporal data) and modelling difficulties (accurate location and timing predictions, considering local geomorphology). Relevant benefits can be derived from relatively small investments in existing multi-hazard coastal warning systems and emerging technologies (Vilibic and others, 2016).

Figure XVII

Pathways connecting the "impacts-disasters" and "mitigation-management-adaptation" components contained in figure I



Source: Prepared by the writing team.

Note: Division by "risk reduction" and governance/institutional/social transformation" adopted from Pinardi and others, 2024.

Cyclone impacts are typically mitigated through different management approaches comprising risk reduction strategies and post-event response and recovery (Hoque and others, 2017). Risk reduction in particular has traditionally mostly involved tackling vulnerability and exposure of coastal assets, infrastructures and communities by means of technological instruments, such as early warning systems, and changes in urban planning and building practices. As these approaches struggle to keep pace with the increasing pressures on coastal areas, new techniques based on geoengineering principles are emerging as potential lines of development for risk reduction to address the characteristics of cyclones as a hazard factor (Miller and others, 2023). In both cases, addressing education, training, involvement of coastal communities and issues related to social acceptance and trust is key to risk reduction.

Sea-level rise and glacial melt

Addressing current coastal impacts, managing future risks and preventing accelerated sea-level rise after 2050 all require immediate mitigation and adaptation (Nicholls and others, 2018). The most urgent adaptation challenge is chronic flooding at high tide (IPCC, 2022). Adaptation planning and implementation needs up to 2050 are projected to increase significantly in most inhabited coastal regions (IPCC, 2019, 2021). Risks can be anticipated and adaptation measures can be planned and implemented over the coming decades, given that adaptation capacity and governance frameworks to manage the risks of projected sea-level rise typically require decades to become effective (e.g. IPCC, 2022; Haasnoot and others, 2021). Without timely action, vulnerable communities will face a reduction in adaptation options and bear disproportionate impacts (IPCC, 2022). Effective responses include decision analysis, land-use planning, public participation and conflict resolution, with the aim of charting adaptive pathways and managing governance challenges posed by sea-level rise (IPCC, 2019). Furthermore, evidence-informed risk management, strengthened stakeholder dialogue and coordination, and enhanced action and support for finance, technology and capacity-building have been prioritized internationally (UNCC, 2025). It is well established that available near-term adaptation options include engineered, sediment- or ecosystem-based protection; land-use planning to reduce vulnerability; and advance (land reclamation) or retreat strategies (relocation) (IPCC, 2019, 2022). Only avoidance and relocation can remove coastal risks for the coming decades, whereas other measures only delay impacts temporarily, have increasing residual risk or perpetuate risk and create ongoing legacy effects and virtually certain property and ecosystem losses (Siders and others, 2019). Large-scale relocation has immense cultural, political, social and economic costs and equity implications, which can be reduced by fast implementation of climate mitigation and adaptation policies (IPCC, 2021, 2022; Haasnoot and others, 2021). Ecosystem-based adaptation, such as planting and conserving vegetation, landward migration and sediment supply, can reduce impacts on human settlements and generate substantial co-benefits across various socioeconomic dimensions, but these measures require space for sediment and ecosystems and have site-specific physical limits (IPCC, 2022; Neijnens and others, 2021; UNFCCC, 2023, 2024b).

Since the main direct impact of glacial melt is its contribution to sea-level rise, strategies are largely covered by the previous paragraph. Beyond that, hazard-specific measures include using geotextiles to cover glaciers (Senese and others, 2020), creating submerged barriers or dams in front of ice sheets and glaciers (Hunt and Byers, 2019) and a wide range of other geoengineering approaches (Lockley and others, 2020).

Coastal erosion, waves and wave run-up, and storm surge and coastal flooding

Mitigating coastal erosion and flooding involves strategies aimed at protecting shorelines, preserving natural landscapes, minimizing the impacts of shoreline retreat on coastal infrastructure and reducing the hazards posed by rising sea levels, storm surges and high tides on coastal communities (IPCC, 2022). Risk mitigation and adaptation strategies should ideally operate across multiple timescales to be effective. In the short term, this includes implementing early warning systems and emergency response protocols and maintaining existing protective infrastructure (Singhvi and others, 2022; Winter and others, 2020). In the medium term, the focus could be shifted to the upgrading of infrastructure, the consideration of nature-based solutions, such as mangrove restoration, and the development of comprehensive coastal zone management plans (Andersson and others, 2022). Long-term strategies may require transformative approaches, such as relocation from high-risk areas (Revell and others, 2021), major infrastructure redesign and strategic rethinking of land-use planning, that account for projected sea-level rise and increased storm intensity and frequency (IPCC, 2022). Successful implementation requires careful alignment of these temporal scales along

adaptation pathways (Haasnoot and others, 2013) with an appropriate multilevel governance framework that spans from emergency response to long-term socioeconomic planning, while ensuring continuity across political cycles (Rocle and others, 2021; Bisaro and others, 2020). Successful risk reduction strategies depend heavily on community buy-in, local knowledge integration and social justice considerations. Vulnerable coastal communities, particularly those with limited resources, often face disproportionate risks while being the least resilient to coastal flooding and erosion (IPCC, 2022).

Marine heatwaves

Well-established impacts of marine heatwaves have been reported for different types of ecosystem, particularly warm-water coral reefs, rocky shores, kelp systems, estuaries, lagoons, mangroves, seagrasses, sandy beaches, semi-enclosed seas, shelf seas and the Arctic region (IPCC, 2022). Socioeconomic systems (including those of Indigenous Peoples and local communities) that rely on these ecosystems are threatened by marine heatwave impacts on incomes, on economic sectors, such as fisheries and tourism, and, in the case of coral reefs, on shoreline protection from waves (IPCC, 2022). Management and adaptation strategies include the use of high-resolution data, forecasts and early warning systems to better prepare for marine heatwave and collect data on their effects (Holbrook and others, 2020; McAdam and others, 2023). These data can be used to guide economic sectors, such as aquaculture, in selecting new sites in order to reduce the likelihood of exposure to marine heatwaves (Sandersen and others, 2020; Liu and others, 2014), and can support active restoration efforts (Fox and others, 2021; Aoki and others, 2020). Early management intervention and shifts in management approaches (e.g. quotas or stock assessments and flexible harvesting strategies) can also help to limit the impacts of marine heatwaves (Le Bris and others, 2018; Pershing and others, 2018; Holbrook and others, 2020). Furthermore, marine protected areas (MPAs) and no-take zones, in addition to terrestrial protection surrounding vulnerable coastal ecosystems, cannot prevent marine heatwaves from occurring. Nevertheless, depending on the location and adherence by people to restrictions on certain activities, the cumulative effect of other stressors on vulnerable ecosystems can be reduced, thereby potentially helping to enhance the rate of recovery of marine life (IPCC, 2022; Arafeh-Dalmau and others, 2023). Moreover, MPAs are more likely to buffer the impacts of marine heatwaves if climate change responses are considered in their design (Smith and others, 2021).

Heavy rainfall and river flooding

Mitigation-management-adaptation strategies against heavy rainfall and river flooding extend beyond coastal zones. Regarding "traditional" defence infrastructure, reinforcing levees, dykes and barriers would protect low-lying coastal areas against coastal, river or compound flooding (Couasnon and others, 2020; Moftakhari and others, 2017), while retention basins and river regulation works would contribute to reducing downstream flooding risks (Winarta and others, 2019). Nature-based solutions (wetlands, mangroves, salt marshes and coastal dunes) can also significantly improve flood resilience, while at the same time enhancing water quality and supporting estuarine biodiversity (Bevacqua and others, 2019; Maiolo and others, 2020). Furthermore, adopting integrated watershed management approaches can prove highly beneficial by controlling erosion, run-off and pollutant loads travelling downstream (Ge and others, 2021), while climate-adaptive infrastructure and planning in coastal cities can enhance the resilience of coastal communities (Wang and others, 2021). Improvements in monitoring, forecasting and early warning system development, along with strategic investment in community preparedness and response, will always be integral to coastal resilience (Figlus, 2022; Shen and others, 2019).

Droughts and saltwater intrusion

Droughts and saltwater intrusion are closely associated in terms of their impacts and therefore call for aligned strategies to strengthen ocean and coastal resilience. In general, aligning water management, land-use policies and coastal zone management should be a key requirement for effective water resources management from catchment to coast. Water conservation measures and efficient crop selection and irrigation practices can alleviate stress on water resources during drought periods (Cook and others, 2018; Tabari and Willems, 2023), while sustainable groundwater management and coastal infrastructure, such as barriers and subsurface dams, can mitigate saltwater intrusion (Werner and others, 2013; Ferguson and Gleeson, 2012). Coastal land-use zoning in vulnerable areas and managed aquifer recharge can also be reliable management strategies (Chong and others, 2014), as can the controlled release of freshwater from upstream reservoirs (Moore and Joye, 2021). Furthermore, ecosystem-based adaptation (restoring

and conserving coastal ecosystems), a shift towards drought- and salinity-tolerant crops in agriculture, and community engagement and education on sustainable water use and irrigation practices can all contribute to resilient coastal ecosystems and communities (Visschers and others, 2022; Mafi-Gholami and others, 2020).

Ocean acidification and ocean deoxygenation

Ocean acidification and ocean deoxygenation generate extensive impacts across ocean-related sectors, including coastal communities, fisheries, mariculture and tourism, and adversely affect all categories of marine ecosystem services – regulating, provisioning and supporting (IPCC, 2022). Adapting to ocean acidification requires enhancing the resilience of marine ecosystems, supporting affected industries and developing adaptive management practices (Pelletier and others, 2020; Trebilco and others, 2022; Woods and others, 2022). With regard to marine heatwaves, the protection and restoration of resilient ecosystems, such as seagrass, mangroves, kelp forests and other benthic habitats, can help to buffer the effects of acidification by absorbing CO_2 and creating more stable local conditions (Falkenberg and others, 2021; Voolstra and others, 2023). Evidence-based support for marine species adaptation, such as selective breeding and diversification of the major aquaculture species, also plays an increasing role (Boudry and others, 2021, Tan and others, 2020). Ocean acidification also affects human health and well-being in the context of malnutrition and poisoning, respiratory issues, mental health impacts and the development of medical resources (Falkenberg and others, 2020). Adapting to ocean changes will require efforts to manage socioecological systems adaptively (Cinner and others, 2019), including for fisheries and aquaculture, by iteratively changing management practices through biodiversity conservation and local management (Doubleday and Connell, 2018; Arkhipkin and others, 2015; Billé and others, 2013; Arafeh-Dalmau and others, 2023).



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Chapter 5
Equity, justice and human rights in the ocean

Key points

- Equity, justice and human rights issues are widespread in the ocean.
- Ocean benefits are inequitably distributed across groups, countries and regions of the world, notably in fisheries, the ocean economy and access to marine ecosystem services.
- Environmental justice concerns are pervasive, as the impacts of marine pollution and plastics, climate change, fishery declines and environmental degradation are disproportionately affecting coastal populations and are inequitably distributed globally.
- Human rights violations are prevalent in the ocean, occurring in fisheries, in the ocean economy, in marine conservation and in relation to a healthy environment and climate change.
- The participation of all affected parties, which is foundational to the achievement of equity, justice and human rights, is needed in ocean governance at all scales, from local to global.
- Existing ocean governance processes lack adequate participation and inclusivity.
- Social equity, justice and human rights are often inadequately integrated into ocean decision-making processes, policies and practices.
- Social equity, justice and human rights are useful frameworks to guide best practices and governance for a sustainable and inclusive ocean.
- States have a key role to play in ensuring that equity, environmental justice and human rights are central to future ocean governance.

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1. Introduction

Humanity has always been deeply connected to, and dependent on, the ocean. This is especially true for coastal populations, island nations and countries adjacent to the ocean. Nevertheless, throughout history, some groups within society and some nations and States have had greater access to, and captured more benefits from, the ocean. Inequities in distribution of the ocean's benefits persist today and are amplified by a growing global demand for ocean resources (Jouffray and others, 2020) and the capture of large shares of the ocean economy by a few corporations and countries (Österblom and others, 2023; Virdin and others, 2021). For instance, global fisheries are dominated by higher-income countries (McCauley and others, 2018; Tickler and others, 2018). Meanwhile, Indigenous Peoples and small-scale fishers often lack adequate access and harvests to earn a livelihood and support adequate nutrition security, despite industrial fleets fishing nearby (Amnesty International, 2023; Andreoli and others, 2023; Environmental Justice Foundation (EJF), 2022).

Simultaneously, climate change, pollution and biodiversity declines are placing increased pressure on the ocean environment, with disproportionate impacts on resource-dependent coastal populations and less wealthy nation States (Bindoff and others, 2019; Intergovernmental Panel on Climate Change (IPCC), 2019, 2021). Toxic pollution from oil development and spills is affecting the environment, fisheries and food security for countless coastal communities worldwide (Andrews and others, 2021; Gill and others, 2012; O'Rourke and Connolly, 2003). Human rights violations are also pervasive in global fisheries (Garcia Lozano and others, 2022; Marschke and Vandergeest, 2016a; Murphy, 2017; Stringer and others, 2016; Teh and others, 2019), in the ocean economy (Bennett and others, 2023b; Figueroa and others, 2023; Lamb and others, 2019; Morgera and Lily, 2022) and in relation to a healthy ocean environment (Bennett and others, 2024).

The above list of issues is emblematic of the widespread and growing inequities, injustices and human rights issues occurring across the global ocean. Meanwhile, efforts have been made to ensure that ocean governance frameworks keep pace with the accelerating environmental changes and declines through an ever-increasing and complex set of institutions, regulations and management efforts (Campbell and others, 2016; Partelow and others, 2023). However, local people and communities have often been inadequately included in ocean governance and decision-making processes, and there has been insufficient attention to equity, justice and human rights in the formulation and implementation of marine policies, management and conservation efforts (Bennett, 2018; Crosman and others, 2022; Österblom and others, 2023).

The present chapter contains a broad overview of the following interconnected substantive and procedural issues: (a) equity in the distribution of the ocean's benefits; (b) environmental justice and the ocean; (c) human rights and the ocean; and (d) participation in ocean governance (see the box for definitions). It concludes with best practices for bringing equity, justice and human rights into the centre of ocean governance.

Definitions of key terms used in the present chapter

Distributional equity: The level of fairness in access to, and benefits from, marine resources and opportunities among groups, countries and regions of the world, which is influenced by historical and contextual factors.

Environmental justice: The distribution of exposure to, and impacts of, environmental hazards and harms, in particular for populations subject to social and structural marginalization.

Participatory ocean governance: Decision-making processes that represent all affected groups and through which equitable opportunities are provided for people to gain access to information, provide input, influence outcomes and seek justice.

2. Equity in the distribution of the ocean's benefits

Society receives a myriad of benefits from the ocean, including food, oxygen, transportation, health, inspiration, recreation, heritage, employment and climate regulation (Grorud-Colvert and Ward, 2023; Isson and others, 2020; Kearney and others, 2023; Lane and Pretes, 2020; Waiti and others, 2022; Wester and others, 2023). However,

marine resources and ecosystem services do not flow to, or benefit, all people equitably (Blasiak and others, 2018; Blythe and others, 2020; Elias and others, 2024; Hicks and others, 2022).

Distributional equity refers to the level of fairness in access to, and benefits from, resources and opportunities derived from coastal and marine environments. Examples of ocean inequities include unequal distribution of fish allocations and catches among countries (Food and Agriculture Organization of the United Nations (FAO), 2024; Hicks and others, 2022); limited and insecure tenure and access rights for small-scale fishers, women and minorities (FAO, 2015a; FAO and others, 2023; Jentoft and others, 2019; Pinkerton, 2019); and limited engagement of low- and middle-income countries in high-seas activities and the consolidation of an ocean economy involving relatively few transnational corporations (Frantzeskaki and others, 2025; Österblom and others, 2015; Virdin and others, 2021).

Some authors argue that inequity is a systemic feature of the ocean economy, embedded in existing political and economic systems that have been shaped by historical legacies of colonialism and exploitation (Clark, 2022; Clark and Cisneros-Montemayor, 2024; Pease, 2021). Current arrangements often favour wealthy and powerful States, corporations and individuals, resulting in benefits accumulated by a few, in harms from development often borne by coastal communities and the most vulnerable, and in considerable disparities in wealth, health, food security and economic opportunities (Österblom and others, 2023; Virdin and others, 2021).

The present part of the chapter serves to further explore how the benefits of the ocean are inequitably distributed across groups, countries and regions of the world, with a focus on three examples for which there is evidence of such inequitable distribution: ecosystem services, fisheries and the ocean economy.

Equity in ecosystem services

Ecosystem services refer to the benefits provided by nature, such as air, water and food, to people (Millennium Ecosystem Assessment, 2005). The benefits of marine ecosystem services, such as fishery production and coastal protection, are often unequally distributed, which has negative impacts on the well-being of coastal communities and groups that are marginalized (Blythe and others, 2020; Drakou and others, 2018). Around the world, local people can find themselves excluded from beaches that they use for recreational, cultural or livelihood purposes (Gould and others, 2022; Middleton, 1988; Montgomery and others, 2015). Native Hawaiians, for example, experience barriers to gaining access to the diverse cultural values provided by beaches as a result of tourism and infrastructure development (Gould and others, 2022).

Many processes and factors, such as insufficient recognition and participation of all user groups in decision-making, insecure tenure rights and a lack of access to resources, contribute to the uneven distribution of coastal ecosystem services and the associated benefits. Tenure and access, for example, are key mechanisms that support benefits from marine and coastal ecosystem services (Fisher and others, 2014; Langemeyer and others, 2024). The erosion of marine tenure undermines local communities' right to have access to their traditional fishing grounds, thereby depriving them of benefits, while exacerbating disparities in wealth and food security (Tholan and others, 2024). Without secure access, communities lack the power to manage and protect their resources (Bennett and others, 2018). Furthermore, disconnection from ancestral fishing practices erodes cultural identity and social cohesion (Patankar and others, 2015).

Equity in fisheries

Global fisheries provide society with multiple social and economic benefits. Fisheries supply 3.2 billion people with a significant portion (>20%) of their protein intake and provide more than 60 million full-time or part-time jobs (FAO, 2024; Teh and Sumaila, 2013).

However, the benefits of fisheries are inequitably distributed among countries. At a global scale, the top eight capture fishery producers (China, Indonesia, India, Peru, the Russian Federation, the United States of America, Viet Nam and Japan) account for more than 51% of the total catch (FAO, 2024). Wealthy countries are responsible for 97% of industrial fishing on the high seas and for 78% within the exclusive economic zones (EEZs) of lower-income countries (McCauley and others, 2018). Heavily subsidized distant-water fishing fleets can deplete stocks that lower-income countries depend on for viable fisheries livelihoods and food security, thus exacerbating existing inequalities (Tickler and others, 2018). Meanwhile, fisheries access agreements often lead to limited economic benefits for host countries (Belhabib and others, 2015; Manach and others, 2013). The industrial fishing aspirations of developing States can be further disadvantaged in regional and international negotiations

owing to international interests in fisheries conservation and catch limits (Andriamahefazafy and others, 2024).

The benefits of fisheries are also inequitably distributed among groups within countries. Small-scale fisheries constitute 90% of the employment in fisheries globally and contribute 40% of the catch (Basurto and others, 2025; FAO, 2023), thereby providing food security and livelihoods to local communities. However, despite their contribution, small-scale fishers continue to be marginalized in decision-making, and their tenure rights continue to be threatened (Islam and Chuenpagdee, 2022). Small-scale fishers often struggle to gain access to and benefit from fisheries due to regulatory barriers, limited access to capital, a lack of technology and limited access to fishing grounds and reduced allocation of catch (Bailey and others, 2016; Pita and Ford, 2023). Small-scale fisheries also lack direct access to markets, and are often dependent on intermediaries, thereby leading to reduced profit margins, whereas larger companies can sell directly to consumers or international markets (Bailey and others, 2016; Pita and Ford, 2023). At the same time, the environmental degradation associated with subsidized overfishing by industrial fleets disproportionately affects the catches and income potential of small-scale fishers (Andreoli and others, 2023; Skerritt and others, 2023).

Equity in the ocean economy

The ocean economy has been growing rapidly and has spurred a rush to claim ocean space and resources (Barbesgaard, 2018; Jouffray and others, 2020; Organisation for Economic Co-operation and Development (OECD), 2016). Although it is claimed that so-called blue economy policies and interventions contribute simultaneously to economic prosperity, environmental integrity and coastal communities (Bennett and others, 2019; Cisneros-Montemayor and others, 2021; Silver and others, 2015), evidence suggests that benefits from the ocean economy are highly inequitable. For example, the 10 largest corporations in eight selected ocean economy industries (including oil and gas, tourism, seafood, wind energy and shipping) generated, on average, 45% of the respective total industry revenues (Virdin and others, 2021). The biggest 100 companies accounted for $1.1 trillion in revenues in 2018, representing 60% of the total (Virdin and others, 2021). Control over growing marine biotechnology markets is also highly concentrated, with a single corporation registering 47% and 10 countries registering 98% of all patented marine genetic sequences (Blasiak and others, 2018).

Despite the promise of jobs and other economic benefits from the development of the ocean economy, local communities may see few of the promised benefits. Oil and gas extraction often produces huge wealth for foreign corporations and national elites; however, the hiring and procurement of goods seldom benefit local communities (Ablo, 2015; Obi, 2010; Oteng-Ababio, 2018). Similarly, shrimp aquaculture, which is resource- and technology-intensive and requires access to global markets, is seldom locally owned and often provides few jobs for local communities and undermines local fisheries livelihoods (Bergquist, 2007; Nickerson, 1999; Primavera, 1997; Stonich and others, 1997). Overlooking social equity in blue growth can lead to accelerated coastal and ocean grabbing processes (Bennett and others, 2021; Das, 2023), which refer to the "dispossession or appropriation of use, control or access to ocean space or resources from prior resource users, rights holders or inhabitants" (Bennett and others, 2015). Highly concentrated economic ownership in the ocean economy thereby leads to "unjust uneconomic growth", which produces few local economic benefits and numerous negative social externalities for local communities (Nogué-Algueró, 2020).

Furthermore, the unequal distribution of benefits is enabled by the exploitation of workers (Campling and Colás, 2018). In 2015, seafarers worked on average 77 hours per week, and investigations uncovered widespread forced labour on fishing vessels (Stringer and others, 2016; Vandergeest and others, 2017). Intense market pressure to reduce costs, combined with weak oversight and accountability for marine industries, has created conditions that enable exploitative labour practices (Campling and Colás, 2018).

Conclusion

The benefits of the ocean are inequitably distributed across groups, countries and regions of the world due to a number of structural and contextual factors. Structural drivers of ocean inequality include: policies that prioritize access, allocation and benefits for industrial fishing fleets over the livelihoods, needs and aspirations of small-scale fisheries; a lack of recognition and enforcement of marine tenure and access for rights holders, including small-scale fishers, Indigenous Peoples and other traditional coastal communities; economic disparities that allow wealthier countries and corporations to exploit a greater share of marine resources; governance mechanisms and decision-making processes

that prioritize the interests of historically industrialized States over the aspirations of developing States; corruption and weak rule of law; and persistent racist and colonial structures that continue to shape ocean policies and practices (Bennett and others, 2022b; Clark and Cisneros-Montemayor, 2024; Frantzeskaki and others, 2025; O'Neill and others, 2025; Österblom and others, 2023; Sparks and Sliva, 2019; Tholan and others, 2024). Inadequate governance and decision-making processes can often exclude persons in marginalized situations and communities, undermining their ability to advocate for access to, benefits from, and sustainable management of their marine resources (Bennett and others, 2018; Bodwitch and others, 2024; Crosman and others, 2022; Strand and others, 2024).

Inequity in the distribution of ocean benefits is driven by and reproduces significant economic disparities, leading to persistent imbalances that undermine local economies, jeopardize food security and exacerbate poverty (Österblom and others, 2023). Additional factors, such as climate change, environmental degradation and global flows of pollution and waste, further exacerbate these inequalities by disproportionately affecting those regions and groups that are dependent on marine ecosystems and have fewer resources to adapt (Prellezo and others, 2023).

3. Environmental justice and the ocean

According to research on environmental justice, populations such as Black and Afrodescendent communities, Indigenous Peoples, women, children and socioeconomically marginalized groups bear a disproportionate burden from polluting industries and waste disposal (Bullard, 1994; Cutter, 1995), climate change and environmental degradation (Brulle and Pellow, 2006; Bullard, 1994, 2018; Cutter, 2012; Sikor, 2013; Tsosie, 2007). Environmental justice issues can affect populations close to the source or in regions of the world far from where the issue is produced.

The present part of the chapter contains an outline of how environmental justice issues related to marine pollution and plastics, climate change, fishery declines and environmental degradation are disproportionately affecting coastal populations and are inequitably distributed globally.

Environmental justice, marine pollution and plastics

Pollution and plastics increasingly infiltrate and affect the ocean. Various pollutants, including persistent organic pollutants (POPs), trace metals, hydrocarbons, sewage, fertilizers, pesticides, flame retardants and pharmaceuticals, enter the ocean from various point and non-point sources (Arias and Botte, 2020; Frid and Caswell, 2017). An estimated 4.8 million to 12.7 million tons of plastic waste, ranging from nanoplastics to macroplastics, are discharged into the ocean each year (Jambeck and others, 2015; Thevenon and others, 2015).

Marine pollutants and plastics harm marine species, fish and biodiversity (Beiras, 2018), as well as the health, food security, livelihoods and well-being of coastal populations (Bowen and others, 2014; Landrigan and others, 2020; United Nations Environment Programme (UNEP), 2021a). For example, toxic substances, such as methylmercury, accumulate in seafood, pose risks that can affect the health and food security of fish-dependent communities, especially women and children (Donatuto and others, 2011; Landrigan and others, 2020; Probyn, 2018). Oil spills, such as the Exxon Valdez and Deepwater Horizon spills, have caused long-term economic and psychosocial damage (Chang and others, 2014; Gill and others, 2012; Palinkas and others, 2004; Picou and others, 2009). In coastal Cameroon, plastic waste now exceeds fish in the catches of small-scale fishers (Suh, 2024).

Some groups (including communities of colour, Indigenous and Afrodescendent groups, women and children) are more exposed and susceptible to the health effects of pollutants (Landrigan and others, 2020; Liboiron, 2021). For example, African-American communities in Louisiana, United States, face disproportionate pollution from offshore oil and gas production (Maldonado, 2018; Randolph, 2021). Inuit women in the Arctic are among the most contaminated humans on the planet due to the persistence and bioaccumulation of POPs in aquatic food chains (Arctic Monitoring and Assessment Programme (AMAP), 2021; Ghisari and others, 2014; Wielsøe and others, 2017). Furthermore, global flows in the disposal of pollution and waste disproportionately affect lower-income countries (Okafor-Yarwood and Adewumi, 2020), which is the case for both shipbreaking and ship disposal (Frey, 2015; Wan and others, 2021) and plastics (Pedra and Gonçalves, 2020; UNEP, 2021b).

Environmental justice and climate change

Anthropogenic climate change is causing changing weather patterns, stronger storms, heatwaves, warming waters, shifting currents and nutrient cycling, deoxygenation and acidification, and sea-level rise (Bindoff and others, 2019; IPCC, 2019). These changes are affecting marine species, including by influencing fish reproduction, growth and distribution (Bindoff and others, 2019; du Pontavice and others, 2020; Morley and others, 2018; Pinsky and others, 2020; Poloczanska and others, 2016) and stressing mangrove, seagrass, saltmarsh and coral reef ecosystems (Bindoff and others, 2019; Doney and others, 2012; Gilman and others, 2008; IPCC, 2022; Klein and others, 2022; Sippo and others, 2018).

Coastal populations are facing direct and indirect climate impacts. For example, changes in fish and shellfish stocks are threatening jobs, revenues and food security (Cheung and others, 2010; Doney and others, 2020; Fernandes and others, 2017; Lam and others, 2016; Narita and others, 2012; Tigchelaar and others, 2021), and rising seas and storms are damaging infrastructure and forcing communities to retreat (Ahmed and Eklund, 2021; Dannenberg and others, 2019; Dasgupta and others, 2022; Hauer, 2017; Heberger and others, 2011; Liwenga and others, 2019; Rahimi and others, 2020; Ryan and others, 2016; Schwerdtle and others, 2018). Displacement of Indigenous coastal communities is disruptive to long-held identities, cultures and traditions linked to the ocean (Weir and others, 2017).

Climate change affects individuals and groups inequitably. Black, Afrodescendent, Indigenous, migrant and low-income populations tend to live in areas more exposed to flooding and storms (Ahmed and Eklund, 2021; Gotham and others, 2018; Hardy and others, 2017) and often have lower capacity to respond (Senapati and Gupta, 2017). Small-scale fishers and Indigenous Peoples are more susceptible to the impacts of climate-related declines in marine ecosystems, ecosystem services and fisheries on livelihoods, food security and culture (Guillotreau and others, 2012; Lauria and others, 2018; Marushka and others, 2019). Adaptation efforts can further marginalize coastal communities, women, Indigenous and Afrodescendent peoples, and persons belonging to minority groups when their voices and needs are excluded or ignored (Bunce and others, 2010; Dannenberg and others, 2019; Sovacool, 2018).

Climate change exposure varies by geography. Coastal communities in Arctic and equatorial regions will likely experience the largest increases in temperatures and changes in the composition of fish species (Asch and others, 2017; Ford and others, 2019; Holbrook and others, 2021; Lam and others, 2016). Countries in Asia, Africa and South-East Asia and the Pacific islands near the equator will be most exposed to impacts on fisheries livelihoods, food security and nutrition (Asch and others, 2017; Golden and others, 2016; Holbrook and others, 2021; Lauria and others, 2018; Tigchelaar and others, 2021). Low-lying, densely populated regions and cities in Africa, Asia and the Pacific are highly susceptible to sea-level rise (Dasgupta and others, 2022; Neumann and others, 2015; Oppenheimer and others, 2019). Moreover, lower-income countries, which are the least responsible for fossil fuel and other pollutant emissions, will suffer most from ocean-related climate impacts (Bindoff and others, 2019; Lamb and others, 2021).

Environmental justice and fishery declines

Globally, fish stocks are in decline due to overfishing, destructive fishing, ineffective management, habitat loss and climate change. An estimated 37.7% of wild fish stocks are fished at biologically unsustainable levels, and the trend of overfishing continues (FAO, 2024; Fromentin and others, 2022). Despite increased fishing efforts since the 1990s (Bell and others, 2017), catch peaked in 1996 and has since declined (Pauly and Zeller, 2016).

The negative impacts of overfishing and fishery declines are unevenly distributed. Indigenous Peoples and small-scale fishers are particularly susceptible to declines in fish and shellfish due to their high reliance on fishing and harvesting for livelihoods and subsistence. Women, whose contributions to fish harvesting, processing and trade are often unrecognized, are particularly affected (Gopal and others, 2020; Harper and others, 2017). In the Pacific, for instance, women account for 56% of small-scale catches (Harper and others, 2013). In Senegal, female traders are severely affected by foreign fishing vessels and the demand of fishmeal factories (Sall, 2024).

Wealthy countries often capture a greater portion of fishery benefits, while driving the declines in fisheries that affect lower-income countries. Distant-water fleets from high-income countries make up 78% of industrial fisheries in low-income countries (McCauley and others, 2018), where seafood provides vital micronutrients that are critical to human health (Hicks and others, 2019). These subsidized fleets undermine the catches, livelihoods and food security of small-scale fishing communities (Andreoli and others, 2023; Skerritt and others, 2023;

Zeller and Pauly, 2019). Illegal, unreported and unregulated (IUU) fishing in West Africa, largely by foreign fleets, accounts for between 30% and 50% of the catch and is driving important food species towards extinction (Daniels and others, 2016; Watkins, 2014).

Environmental justice and environmental degradation

Marine habitats are being destroyed and ecosystems are being degraded at alarming rates. For example, an estimated 19% of seagrasses, 30% of coral reefs, 35% of mangroves and 50% of salt marshes have been lost or degraded (Barbier, 2017; Dunic and others, 2021; Romañach and others, 2018). Human activities threaten ecosystems and the essential goods and services they provide (Bindoff and others, 2019; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019, 2024), including food, medicine, livelihoods, carbon sequestration, storm protection, cultural heritage, health and well-being (Barbier and others, 2011; Blythe and others, 2020; Cisneros-Montemayor and others, 2016; Costanza, 1999; Cullen-Unsworth and others, 2014; Islam and others, 2020; Woodhead and others, 2019).

However, these losses and their impacts vary across groups and geographies and are not felt equally. Indigenous populations in the Canadian Arctic are directly affected by the changes in the distribution, health and abundance of beluga populations, which are central to their diets and culture (Loseto and others, 2018). Low-income coastal countries are more vulnerable to the effects of climate change on coral reef fisheries and food security (Hughes and others, 2012). Future losses of coastal protection will likely have the biggest impact on Africa and South-East Asia (Chaplin-Kramer and others, 2019).

Conclusion

Environmental justice issues are widespread across the world's oceans (Bennett and others, 2023a; Blythe and others, 2023). The effects of marine pollution and plastics, climate change, fishery declines and environmental degradation are inequitably distributed across social groups and geographies. Groups and countries with strong ties to, and a high reliance on, the ocean are more exposed and vulnerable to the effects of these environmental issues. That situation is compounded for groups that are subject to historical or ongoing social, economic or political marginalization, including various racial groups, Indigenous Peoples, women, younger persons, migrants and groups with lower socioeconomic status (Bennett and others, 2023a; Blythe and others, 2023).

Many environmental justice issues are often localized, stemming from weak environmental laws, poor implementation, or the lack of accountability in ocean economy development or resource harvesting and management. At the same time, global environmental injustices exist in the ocean, as some regions face more pollution, overfishing, environmental degradation and climate impacts (Bennett and others, 2023a). These issues persist due to the continuation of global practices that enable high consumption in wealthy countries to drive resource extraction, waste dumping and climate change impacts in less wealthy regions of the world (Liboiron, 2021; Okafor-Yarwood and Adewumi, 2020).

4. Human rights and the ocean

Under international law, a universal set of human rights that underpin human dignity and security is acknowledged. In the International Bill of Human Rights, which includes the Universal Declaration of Human Rights of 1948 (United Nations, 1948), it is recognized that all people have a fundamental set of civil, political, economic, social and cultural rights (United Nations, 1976, 1966). The responsibility of society to safeguard the human rights of individuals that belong to groups subject to discrimination (ethnic, religious and minority groups) and vulnerable groups (women, children, older persons and persons with disabilities) is further clarified in subsequent conventions (United Nations, 1965, 1979, 1989, 2006).

In the United Nations Declaration on the Rights of Indigenous Peoples and the United Nations Declaration on the Rights of Peasants and Other People Working in Rural Areas, Indigenous Peoples and traditional communities are recognized as having unique rights associated with their status and connection to the environment (United Nations Human Rights Council, 2018; United Nations, 2007). The General Assembly has recently recognized the human right to a clean, healthy and sustainable environment and that clean air, a safe and stable climate, healthy ecosystems and biodiversity, safe and sufficient water, non-toxic environments, and healthy and sustainable food are necessary for the realization of other human

rights (e.g. to life, health, food, livelihoods and security) and the rights of specific groups, namely Indigenous Peoples, small-scale fishers, women and children) (United Nations, 2022). Countless other international instruments and frameworks, including on human rights (e.g. the Convention on the Elimination of All Forms of Discrimination against Women (United Nations, 1979)), on labour (e.g. the International Convention on the Protection of the Rights of all Migrant Workers and Members of their Families (Office of the United Nations High Commissioner for Human Rights (UN OHCHR), 1990) and the Work in Fishing Convention, 2007 (No. 188) (International Labour Organization (ILO), 2007) and voluntary guidelines (e.g. the *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* (FAO, 2015b) and the *Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security* (FAO, 2012)) are also relevant in the context of oceans, and are too numerous to review comprehensively here.

Human rights are universal; they apply to everyone, everywhere, including in marine and coastal environments (Barnes and others, 2018; Bennett and others, 2024). However, human rights violations are rife in the ocean. The substantive human rights issues in fisheries, the ocean economy and marine conservation and in relation to a healthy ocean are examined below.

Human rights issues in fisheries

Human rights violations are widespread in fisheries. Evidence of trafficking in persons, forced labour, child labour and alarming working and living conditions on fishing vessels have been uncovered through journalism and research (Teh and others, 2019; Urbina, 2019). While such violations first emerged in South-East Asia (EJF, 2013; ILO, 2013a; Levitt, 2016), subsequent investigations have uncovered abuses across the globe (Lawrance and others, 2015; Marschke and Vandergeest, 2016b; Murphy, 2017; Stringer and others, 2016).

Fishers are vulnerable to human rights abuses due to numerous conditions inherent to the sector: isolation, length of time at sea, transnational operations and restricted labour supply (ILO, 2013b). Migrant workers are especially vulnerable in some places and situations due to unregulated recruitment, the withholding of identity documents, debt bondage and an absence of the right to organize (Marschke and Vandergeest, 2016b; Murphy, 2017). These issues have been notoriously difficult to address owing to the complexity of fisheries, the vastness of the ocean and the intersection with organized crime (Belhabib and Le Billon, 2022; Witbooi and others, 2023). Of note, the Western and Central Pacific Fisheries Commission recently adopted the world's first binding minimum standards for crew labour conditions by a regional fisheries management organization (RFMO) (Haas and others, 2024), thereby setting an important global precedent.

Furthermore, human and labour rights violations occur across the supply chain (Garcia Lozano and others, 2022; Nakamura and others, 2018), with a particular impact on women, who make important contributions in the post-harvest sector, including in processing and trading (FAO, 2023). Gender roles and systemic discrimination across different cultural contexts lead to increased risk and vulnerability for women in fisheries (Manyungwa and others, 2019), including gender-based and sexual violence (Lowen, 2014; Mangubhai and others, 2023; Nathenson and others, 2017; Yadao-Evans and Kauhiona, 2019). Despite representing 40% of fish workers globally (FAO, 2023), women are often "invisibilized" (Harper and others, 2013) and excluded from human rights protection efforts in fisheries (Finkbeiner and others, 2021).

Numerous pervasive human rights issues also affect small-scale fisheries globally (Allison and others, 2011; Sharma, 2011; Teh and others, 2019), including food and livelihood insecurity resulting from overfishing by foreign fleets (Aheto and others, 2020; EJF, 2019; FAO, 2021; Finkbeiner and others, 2021; Simmons, 2023); the erasure of traditional knowledge and cultural practices; and forced eviction from, or disrupted access to, territories, lands and waters (Ratner and others, 2014; Sharma, 2011). These issues emerge in large part due to inadequate recognition of, attention to and protection of small-scale fishers' human, tenure and access rights in fisheries management (Cohen and others, 2019; Figueroa and others, 2023). Women, Afrodescendent populations and Indigenous Peoples involved in small-scale fisheries are often disproportionately subject to exclusionary and punitive practices (Galappaththi and others, 2022; Jentoft and others, 2019; Mbatha, 2022; Satizábal, 2018).

Another source of human rights violations in small-scale fisheries is when management measures put in place by States to address overfishing and IUU fishing undermine the rights of small-scale fishers and lead to their criminalization (Song and others, 2020).

Human rights issues in the ocean economy

There is growing evidence that various sectors, including the aquaculture industry, across the broader ocean economy have undermined human rights in different ways. According to a sector-wide impact assessment of salmon farming in Chile, the aquaculture industry is infringing on labour rights, the right to a healthy environment and the rights of Indigenous Peoples (Fuentes and others, 2021). Simultaneously, aquaculture feed relies in large part on industrial fishing practices and fishmeal factories, which in certain regions, including West Africa, are contributing to overfishing of small pelagic fish stocks and the undermining of local fisheries and the rights to livelihoods and food security (Cashion and others, 2017; Jobe, 2023; Koigi, 2019; Sall, 2024).

Spatial displacement, dispossession and appropriation are also common features of the ocean economy that undermine the tenure and access rights of coastal communities, small-scale fishers and Indigenous Peoples (Bennett and others, 2021; Cohen and others, 2019; Narchi and others, 2024). Ocean and coastal grabbing is prevalent in sectors such as aquaculture, coastal tourism, oil infrastructure development and post-disaster reconstruction (Barbesgaard, 2018; Bavinck and others, 2017; Bennett and others, 2015; Franz and others, 2024; Mesmain, 2014; Narchi and others, 2024; Owusu and others, 2023; Silva and Pierri, 2024). The rapid global expansion of shipping and port infrastructures has displaced communities and small-scale fishers from traditional fishing sites, which affects their rights to food and livelihoods, particularly in Africa and Latin America (Contested Ports, 2020; Lawer, 2019; Okafor-Yarwood and others, 2020).

Violence against local people and ocean defenders – individuals and groups that are organizing and taking action to resist developments that threaten the ocean environment and their human rights – is prevalent in some places where dispossession, displacement, ocean grabbing and conflict result from development pressures, thereby threatening the rights to security of the person and to life (Bennett and others, 2022a, 2023b; The Ocean Defenders Project, 2025).

Human rights violations will continue to occur in the rapidly accelerating ocean economy if States and businesses do not take their obligations and responsibilities to respect, protect and fulfil human rights seriously.

Human rights issues related to a healthy ocean

Mounting anthropogenic pressures on the ocean environment also threaten the right to a clean, healthy and sustainable environment (Bennett and others, 2024; Puentes Riaño, 2024; United Nations, 2022). Human rights to a healthy ocean are being undermined by marine pollution and plastics, the effects of climate change, degradation of habitats and biodiversity and fishery declines (Bennett and others, 2024; Landrigan and others, 2020; Puentes Riaño, 2024).

Oil exploration and extraction, for example, produce pollution that affects the rights to livelihoods, food and health of small-scale fishing communities globally (Andrews and others, 2021). In Quintero-Puchuncaví Bay, Chile, communities have endured decades of pollution from a sacrifice zone, where thermoelectric, petrochemical, oil refining, chemical and copper processing plants are concentrated, undermining their ability to live in a non-toxic environment with healthy food and clean air (Galaz, 2021; Panez and others, 2023; Valenzuela-Fuentes and others, 2021). The prevalence of plastics in the ocean and on beaches threatens the right of young people and future generations to be able to experience and live in clean environments (O'Meara, 2023).

Climate-related changes, including ocean warming, acidification, extreme weather, sea-level rise and storm surges, are affecting safe and stable climate conditions, which are foundational to the rights to food, livelihoods, security and life (Bennett and others, 2024; Bindoff and others, 2019; IPCC, 2021; Puentes Riaño, 2024). This is particularly true for people who are highly reliant on marine resources, those living in low-lying coastal cities and residents of small island developing States (Bennett and others, 2023a).

A growing number of national court cases worldwide have featured arguments related to the right to a healthy environment in order to halt threats to fishing activities (Davide, 1997; Vasquez, 2023), to stop the development of a major coal port (Nyamweya and others, 2018), to stop oil and gas exploration (Mbenenge, 2022) and to mandate restoration (Velasco, 2008). Nevertheless, a concerning emerging trend is that ocean defenders who speak up for the protection of the human right to a healthy ocean are being marginalized, silenced, threatened and even murdered for their efforts (Bennett and others, 2023b).

Human rights violations in marine conservation

Evidence of concerning practices by Governments and non-governmental organizations in the name of conservation (including substantive and procedural human rights violations and rights violations specific to Indigenous Peoples and women) began to emerge in the early 2000s (Agrawal and Redford, 2009; Brockington and others, 2006; Brockington and Igoe, 2006; Chapin, 2004; Springer and others, 2011; Tauli-Corpuz, 2016; West and others, 2006). Prevalent human rights violations in the context of the conservation of terrestrial wildlife and ecosystems are related to the lack of participation in decision-making or free, prior and informed consent, forced displacement and restrictions on resource access, and impacts on the rights to livelihoods, food and culture, among others (Springer and others, 2011).

Recently, however, scholars have highlighted the pervasiveness of human and Indigenous rights issues in marine conservation (Smallhorn-West and others, 2023). For example, marine protected areas (MPAs) designated in the context of historical injustices associated with apartheid in South Africa, along with a failure to address ongoing inequities, have resulted in the weakening of local governance rights and processes, the loss of tenure rights and access to resources, and the loss of culture and sense of place (Sowman and Sunde, 2018).

Evidence of displacement and dispossession through inappropriate conservation and management measures, referred to as ocean grabbing (Bennett and others, 2015), exists across many different contexts, such as in Guinea-Bissau (Cross, 2016), Malaysia (Hill, 2017) and the United Republic of Tanzania (Kamat, 2018).

Although some violations persist, and there is a need for restitution and remedial action in many places, conservation organizations have recognized and taken numerous measures to address past issues related to human rights in marine conservation. Notably, the importance of respecting and protecting human rights, including Indigenous rights, and taking a human rights-based approach to conservation is acknowledged in the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity (CBD), 2022). Global conservation organizations and Governments have made progress by implementing environmental and social safeguards, improving participation and increasing benefit-sharing mechanisms, as well as advancing support for conservation initiatives led by Indigenous Peoples and local communities (Ford-Learner and others, 2024; Smallhorn-West and others, 2023).

Conclusion

States have an obligation, and businesses have a responsibility, to promote, respect and protect human rights in relation to the ocean, from coastal margins to the high seas (United Nations Human Rights Office of the High Commissioner, 2011; United Nations, 1998). Nevertheless, numerous human rights violations persist in fisheries, in the ocean economy and due to threats to a healthy ocean environment. Furthermore, marine conservation and fisheries management approaches often inadequately consider human rights. Despite the growing recognition of human rights issues that occur in marine and coastal environments, many national and international ocean governance frameworks and processes still lack explicit recognition of, and a requirement to address, human rights (Bennett and others, 2024).

5. Participation in ocean governance

Participation in governance is foundational to the realization of equity, justice and human rights in the ocean. The achievement of more equitable distribution of the ocean's benefits and the reduction of environmental injustices, for example, are enabled by the recognition and representation of diverse groups in ocean governance processes (Bennett and others, 2023a; Spalding and others, 2023).

The realization of substantive human rights related to a healthy ocean also requires attention to procedural elements, which include access to information, public participation in decision-making and access to justice (Bennett and others, 2024; United Nations, 2022). Regional agreements, such as the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters and the Regional Agreement on Access to Information, Public Participation and Justice in Environmental Matters in Latin America and the Caribbean (Economic Commission for Europe (UNECE), 1998; United Nations, 2018), underscore the importance of participation of all affected parties in environmental matters as a matter of human rights.

Participatory ocean governance requires all rights holders and stakeholders to be recognized, all affected actors and diverse perspectives to be included, and insights from natural science, social science and traditional knowledge to be represented in decision-making

(Gosnell and others, 2025; Haas and others, 2023). Particular attention is needed to ensure that formerly excluded or silenced populations, such as Indigenous Peoples, small-scale fishers and women (Strand and others, 2024; Intergovernmental Oceanographic Commission and the Local and Indigenous Knowledge Systems programme of the United Nations Educational, Scientific and Cultural Organization (UNESCO-IOC and UNESCO-LINKS), 2024), are effectively included in ocean governance, planning and management processes (Strand, 2023). Inclusion must not be tokenistic, but rather influence and shape policies and management (Bennett and others, 2021; Flannery and others, 2018; Rivers and others, 2023).

The extent to which ocean governance processes are participatory, at various scales, is examined below.

Participation in national and local ocean governance

Over the past few decades, there have been increasing efforts to make marine conservation, fisheries management and ocean economy planning processes more participatory. In practice, however, ocean governance at national and local scales varies substantially in terms of the level and quality of participation.

Acknowledging and including a diversity of actors, including Indigenous Peoples, local communities, small-scale fishers, women's groups and other local groups, are key to achieving participatory local and national ocean governance processes (Short and others, 2021). Nevertheless, in the context of marine conservation, for example, Indigenous and local communities often continue to be excluded from planning and management of MPAs, for example (Gill and others, 2023; Smallhorn-West and others, 2023).

In South Africa, decision-making processes related to the establishment and management of MPAs have excluded subsistence and small-scale fishers, and Indigenous and coastal communities (Peer and others, 2022; Sowman and Sunde, 2018; Strand, 2023). On the other end of the spectrum is Haida Gwaii in Canada, where plans for marine protection, stewardship and governance have been co-developed between the Indigenous Haida Nation and the provincial government of British Columbia, with representation from the Haida governing council (Jones and others, 2024).

In general, advances in national policies aimed at improving participation and inclusion in fisheries have taken the forms of co-management (Cinner and others, 2012). For instance, in Chile, the progressive institutionalization of co-management has included introducing territorial user rights for fisheries (TURFs) in 1991 (Gelcich and others, 2010, 2012), creating collective action arenas in 2013 (Gelcich and others, 2019) and adopting voluntary conservation areas by artisanal fishers in 2024. In 2011, Belize committed to establishing territorial user rights for fisheries called "managed access areas" throughout its territorial sea (i.e. its exclusive economic zone) through two pilot sites at Port Honduras and Glover's Reef marine reserves, which were scaled up to ensure fishing rights for small-scale operators and communities throughout its territorial sea (Fujita and others, 2017, 2019). In Peru, a co-management scheme was introduced for the profitable scallop mariculture sector in order to address significant challenges relating to management, corruption, pollution and enforcement of rules (López de la Lama and others, 2018).

Fisheries co-management processes in different countries have been more or less successful at incorporating the various elements necessary for effective participation, which include policymaking processes that are co-produced and include fishers (Barceló and others, 2024; Sorice and others, 2018), clear roles and adequate capacity (Estévez and others, 2021), integration of diverse knowledge systems (Norström and others, 2020), support for local stewardship (Bennett and Satterfield, 2018) and agency for managing seascapes (Bandura, 2000). Nevertheless, women are often inadequately included in fisheries decision-making processes (Lawless and others, 2021; Mangubhai and Lawless, 2021).

Participation in international and regional ocean governance

At the international level, the limited agency of less powerful States and the level of civil society participation in ocean governance processes are concerning. For example, the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction was adopted in 2023 under the auspices of the United Nations and addresses issues related to environmental impact assessments, area-based management tools, including MPAs, capacity-building and technology transfer, and marine genetic resources, including benefit-sharing. Despite lengthy negotiations intended to balance various interests and priorities, the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction process has been critiqued for offering limited opportunities for the participation of

civil society, Indigenous Peoples and other interested non-State actors (Morgera and others, 2022; Strand and others, 2022). There have also been significant inequities in terms of participation, representation and influence of States with smaller economies (Sparks and Sliva, 2019).

Most of the world's oceans are now covered by at least one RFMO, and the United Nations Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks institutionalizes the duty to cooperate and requires all Parties to apply conservation and management measures established by existing RFMOs. Under the Fish Stocks Agreement, access to straddling fish stocks and tuna fisheries is limited to Parties that at the very least agree to implement the RFMO measures. RFMOs have the potential to increase the participation and agency of less wealthy and powerful States in ocean governance (Sinan and others, 2022). However, it could be argued that RFMOs have not adequately considered the interests of smaller or emerging economies, particularly with regard to the equitable allocation of fishing opportunities and the disproportionate burdens of conservation measures, which often favour historically developed fishing States over developing States (Seto and others, 2021; Seto and Hanich, 2018; Sinan and others, 2022) or non-State actors, such as Indigenous Peoples and local communities. Nevertheless, there have been positive developments in RFMOs, such as the Western and Central Pacific Fisheries Commission, in which collective bargaining by small island developing States has helped to ensure that their interests are more effectively considered.

Under the Fish Stocks Agreement, there is a need to avoid adverse impacts on, and ensure access to fisheries by, subsistence, small-scale and artisanal fishers, women fish workers and Indigenous Peoples, and Parties must avoid transferring, directly or indirectly, a disproportionate burden of conservation action onto developing States (United Nations, 1995). Unfortunately, however, only the Western and Central Pacific Fisheries Commission has adopted any measures to explicitly implement this requirement in practice (Western and Central Pacific Fisheries Commission (WCPFC), 2013).

Conclusion

A major challenge for the realization of equity, justice and human rights is ensuring effective participation in ocean governance processes. Although progress is being made in local and national ocean governance processes, inclusivity in regional and international ocean governance processes is still limited. In particular, lower- and middle-income States have less power and voice in regional and international ocean governance processes, and the opportunities for civil society organizations and groups to participate and contribute are limited.

In general, certain groups, including Indigenous Peoples and small-scale fishers, continue to be underrepresented in local and international approaches to ocean governance (Spalding and others, 2023). Furthermore, legacies of colonialism and levels of development continue to have an impact on who is involved, what knowledge systems and values are considered, and the overall quality and equity of ocean governance processes (Spalding and others, 2023; Strand and others, 2024).

6. Overall conclusion

In the present chapter, equity, justice and human rights issues in the ocean are examined. Benefits from fisheries, ecosystem services and the ocean economy are inequitably distributed among groups, countries and regions of the world. Marine pollution and plastics, climate change, environmental degradation and fishery declines disproportionately affect certain groups and geographies. Human rights violations occur in fisheries, the ocean economy, marine conservation and in relation to a healthy environment.

Behind these omnipresent issues are an ocean economy that prioritizes the economy over human well-being; power asymmetries driven by wealth accumulation and colonial histories; increasing privatization and consolidated ownership of the ocean economy; and ocean governance processes that overlook equity, justice and human rights. Although current levels of participation in ocean governance processes remain largely insufficient to lay the necessary foundation for the achievement of equity, justice and human rights, there is significant potential to strengthen future ocean governance.

Best practices

In that context, below are five best practices for how equity, justice and human rights can be placed at the centre of ocean governance and management.

1. **Recognize the unique relationships, dependence and rights of diverse peoples in relation to the ocean.** Humanity depends on the ocean; however, different groups have unique relationships with it. To lay the groundwork for effective participation and the promotion of equity, justice and human rights in ocean governance, society must formally acknowledge how diverse individuals, groups, communities, countries and nations relate to, rely on and have rights to the ocean, and integrate these considerations into ocean governance. For example, different communities depend on marine ecosystem services to a greater or lesser extent for various aspects of well-being. Coastal Indigenous Peoples and small-scale fishers have deep cultural connections that depend on access and tenure rights, but those rights are often unrecognized or have been eroded. A social science perspective, grounded in traditional and local knowledge, could support the integration of social considerations into ocean governance.
2. **Ensure equitable representation and meaningful participation in ocean governance processes at all scales.** Participation is foundational to achieving equity, justice and human rights in ocean governance, and is a key pathway to achieving sustainability. However, there are major shortcomings in the level of inclusivity and participation in local, national and international ocean governance. Under international human rights law, the participation of all affected parties in environmental decisions, underpinned by access to information and access to justice, is mandated (UNECE, 1998; United Nations, 2018, 2022). Explicit recognition and representation of all stakeholders and rights holders is a first step towards more equitable governance processes. Effective participation requires transforming social cultural norms and addressing various procedural elements, including access to information, funding, capacity, facilitation, accountability and conflict resolution, in order to avoid tokenistic participation and ensure that all groups can influence decision-making.
3. **Pursue equity in the distribution of benefits from the ocean.** Without adequate controls, there is a risk that the ocean economy could exacerbate inequality, thereby undermining the achievement of the Sustainable Development Goals related to decent work, poverty reduction, gender equality and food security (Österblom and others, 2023; United Nations, 2015). Addressing inequalities requires ocean governance policies, processes and practices to prioritize human well-being alongside environmental sustainability. Practical policy measures include social impact assessments, benefit-sharing mechanisms, the implementation of tenure and access rights for coastal communities, and gender equality practices. Tackling corruption, impunity and tax evasion and enforcing fair labour practices are also essential. These solutions must consider actions to address systemic inequities in ownership and seek redress for historical disadvantages.
4. **Address the drivers, sources and disproportionate impacts of environmental injustices in the ocean.** Certain segments of society and regions of the world bear the brunt of marine environmental issues. At the highest level, bold policies and actions are needed to address the root drivers of each of the growing issues that are leading to environmental injustices – marine pollution and plastics, climate change, fishery declines and environmental degradation. Governments must create and enforce environmental policies and management actions to lessen the burden on the oceans by, for example, banning chemical pollutants, curtailing point source and non-point source pollution, reducing plastic production and improving waste management, and addressing overfishing. Corporate actors might also be further incentivized or forced to improve technologies and the sustainability of their practices (Blasiak and others, 2021; Österblom and others, 2022). It could be argued that environmental justice issues in the ocean also persist due to enduring racism, colonialism and a capitalist economy that enables inequitable global flows of resources to wealthy countries and waste to less wealthy countries. These challenging issues must be brought into question.
5. **Embed human rights in national and international ocean governance frameworks and management practices.** Under international human rights treaties and law, Governments have an obligation, and businesses and other civil society organizations have a responsibility, to promote, respect, protect and fulfil human rights (Bennett and others, 2024; Knox, 2018; Puentes Riaño, 2024; United Nations Human Rights Office of the High Commissioner, 2011). This applies both within territorial seas and in areas beyond national jurisdiction. Despite some progress, human rights agreements and obligations should be more explicitly acknowledged in global ocean governance processes and agreements (Bennett and others, 2024), and national marine policies and management

practices (e.g. related to marine conservation, fisheries and the ocean economy) must contain improved recognition and provisions to protect human rights. Businesses engaged in the ocean economy must uphold human rights in their operations and supply chains, and States are obliged to regulate, monitor and prevent human rights abuses by the private sector (United Nations Human Rights Office of the High Commissioner, 2011). States and civil society organizations should adopt human rights-based approaches, including requiring economic and social impact assessments and free, prior and informed consent, in fisheries management, marine conservation, and restoration and climate adaptation efforts (One Ocean Hub, 2023; Smallhorn-West and others, 2023). The tenure and access rights of Indigenous Peoples and small-scale fishers should be acknowledged and respected in ocean governance (FAO, 2012, 2015b; United Nations Human Rights Council, 2018; United Nations, 2007). Ocean defenders must be safeguarded in their right to gather, organize and advocate for the ocean, their territorial rights and human rights.

Lastly, all duty bearers – Governments, businesses and civil society organizations that have obligations and responsibilities – must be held to account for not upholding human rights related to the ocean (Smallhorn-West and others, 2023).

In summary, this chapter has served to highlight the types and scope of ocean-related distributional inequities, environmental injustices and human rights violations. Future ocean governance requires a fundamental shift to place equity, justice and human rights at the centre of ocean policy, management and sustainability efforts. States have a responsibility to ensure inclusive and participatory decision-making and management, to promote the equitable distribution of benefits from the ocean, to address environmental injustices and to embed human rights in ocean governance frameworks. Creating robust ocean policy frameworks and implementing concrete and effective management actions regarding these priorities are essential to upholding broader international commitments related to human rights and sustainable development.



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Chapter 6
Gender

Key points

- Persistent gender disparities across ocean sectors: women remain underrepresented in ocean-related employment and decision-making processes. Traditional roles often restrict their participation in fisheries, aquaculture, maritime industry and marine sciences, perpetuating inequalities in resource access, leadership opportunities and economic outcomes (Crosman and others, 2022; Johannesen and others, 2022).
- Importance of gender-transformative governance: integrating gender perspectives into ocean governance enhances the resilience and effectiveness of conservation and management initiatives. Women's knowledge, particularly in small-scale fisheries and coastal communities, is an underutilized resource that can enrich governance frameworks and promote sustainable outcomes (Andrade and others, 2021; De la Torre-Castro and others, 2017) (see also subsect. 5A, subchap. 1B).
- Advances and gaps in gender integration: milestones, such as the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction of 2023, demonstrate progress in recognizing gender in international frameworks. However, systemic challenges, including a lack of gender-disaggregated data and entrenched masculinized cultures, limit the implementation of gender-responsive policies (Kitada and Rodríguez-Chaves, 2024; Hornidge and others, 2023).
- Need for intersectional approaches: addressing gender issues in ocean governance requires intersectional strategies that take into account the ways in which factors such as ethnicity, class and geography intersect with gender. These approaches are vital to tackling systemic barriers and fostering equitable participation in ocean-related activities (Axelrod and others, 2022).
- Benefits of gender-transformative conservation: case studies show that gender-transformative approaches in marine conservation lead to more gender-equitable decision-making and innovative strategies. Promoting women's leadership in ocean science and governance is aligned with sustainable practices and strengthens community resilience (Giakoumi and others, 2021; Shellock and others, 2022).

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1. Introduction

Gender plays a critical role in shaping ocean-related employment, activities and governance. However, systemic disparities continue to limit equitable access and representation in these sectors. Women are often underrepresented in leadership positions and decision-making processes, while traditional gender roles restrict their participation in fisheries, aquaculture and marine sciences (Crosman and others, 2022; Johannesen and others, 2022). Addressing these inequities is essential to fostering sustainable and inclusive ocean governance (Bennett, 2022).

Achieving the Sustainable Development Goals, particularly Goal 5, on gender equality, requires the integration of gender considerations into ocean policies and frameworks. A gender-responsive approach not only supports social justice, but also enhances the effectiveness of conservation and management initiatives by drawing on women's extensive, yet often underutilized, knowledge of marine ecosystems. This is especially relevant in small-scale fisheries and coastal communities (Andrade and others, 2021; De la Torre-Castro and others, 2017). Such an approach enriches governance systems, ensuring resilience and sustainability in the face of global challenges.

Despite this recognition, progress remains limited. Differences in systematically collected, gender-disaggregated data represent a critical gap that hampers the design of targeted interventions aimed at achieving equitable access and participation in ocean sectors (Kitada and others, 2023). Research on the gender-ocean nexus has predominantly been focused on women's roles and has often overlooked the impacts of masculinities and the entrenched masculinized cultures that exclude women and other marginalized people (Hornidge and others, 2023). Addressing these dimensions is key to dismantling structural barriers and fostering inclusive policies.

Recently, there have been significant milestones in international ocean governance, such as the inclusion of gender-responsive language in the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. This Agreement, the first law of the sea instrument in which gender is explicitly addressed, reflects the cross-cutting importance of gender in sustainable ocean management (Kitada and Rodríguez-Chaves, 2024). Such progress is aligned with a growing recognition that gender perspectives must be integrated into global frameworks aimed at promoting equity and inclusivity across sectors (the dimensions of equity are further explored in subsect. 5B, chap. 5).

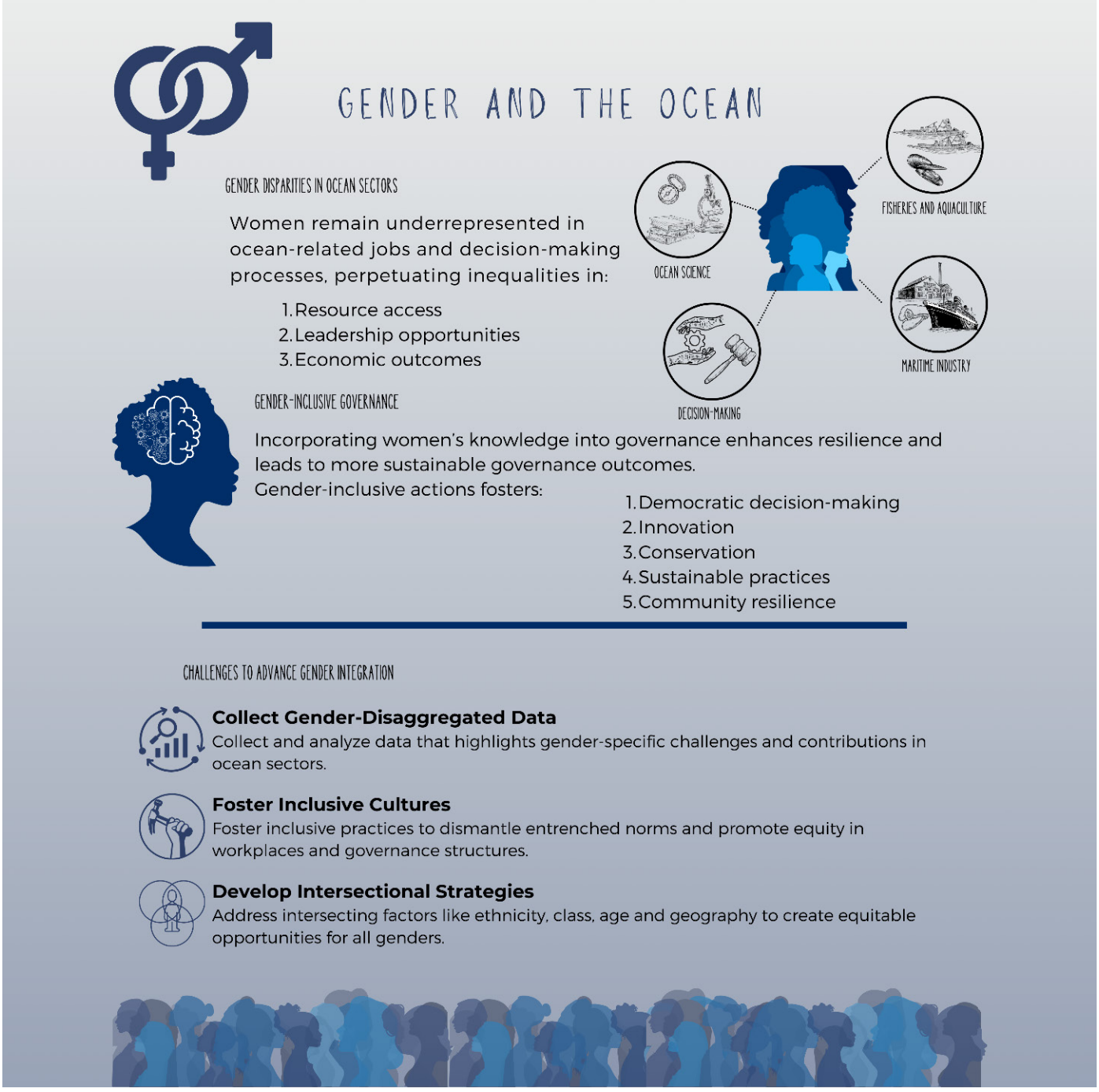
The intersection of gender and social, economic and environmental dimensions further underscores the need for a comprehensive approach. Traditional gender roles have historically influenced activities in marine environments, ranging from fishing (Mangubhai and others, 2022) and aquaculture (Kruijissen and others, 2018) to governance and research (Crosman and others, 2022; Johannesen and others, 2022). Through international initiatives, organizations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO) are emphasizing the need for structural changes aimed at promoting gender diversity in marine science and technology in light of its importance for fostering innovation and addressing global challenges (IOC-UNESCO, 2020).

The present chapter focuses on the role of women in the context of ocean employment and activities, and provides an in-depth examination of gender-responsive approaches to ocean governance. Including these discussions in the *World Ocean Assessment* makes it possible to highlight the importance of gender awareness and inclusive policies. The chapter also provides actionable insights for embedding gender equality within global ocean governance frameworks, drawn from case studies.

Three case studies were deliberately selected because each project was supported by a prominent international organization that coordinates activities in its sphere of work, exemplifying how structured global collaboration can drive gender-responsive practices. While other sectors – such as offshore oil, gas, renewable energy, tourism, recreation, environmental protection and coastal management – also play critical roles in the ocean economy, focusing on these three cases facilitates an in-depth exploration of coordinated international efforts in promoting gender equality.

Figure I

Gender and the ocean: overview of gender disparities in ocean-related sectors and the role of gender-inclusive governance in promoting sustainability, equity and resilience



Source: Prepared by the writing team.

2. Gender and the Sustainable Development Goals

The Sustainable Development Goals of the 2030 Agenda for Sustainable Development build on the foundation of the Millennium Development Goals, which provided a framework for development and resulted in significant progress in several areas. However, the Millennium Development Goals had a limited scope and relatively few indicators, leading to uneven progress on some Goals; the Sustainable Development Goals were designed to complete what remained unachieved (see General Assembly resolution 70/1). The Sustainable Development Goals are grounded in frameworks such as the Beijing Declaration and Platform for Action and the Programme of Action of the International Conference on Population and Development, and contain an emphasis on the causal role of discriminatory laws, beliefs and practices in relation to ocean and gender disparities (Odera and Mulusa, 2020). The focus on gender is evident in Goal 5, "Achieve gender equality and empower all women and girls", and in the cross-cutting consideration of gender issues in other Goals (Fukuda-Parr, 2016; Leal Filho and others, 2023). Gender equality is thus recognized as critical for economic, social and environmental sustainability (United Nations, 2024), with direct impacts on the implementation of the 2030 Agenda.

Although Sustainable Development Goal 14 does not explicitly address gender, the interdependence of the Goals demands that gender considerations shape the conservation and sustainable use of ocean resources (Breuer and others, 2019; International Council for Science, 2017). Achievement of the targets under Goal 14 is significantly affected by gender disparities (Leal Filho and others, 2023). The intersection between Goals 5 and 14 illuminates the importance of integrated approaches that enhance gender equality and advance sustainable ocean management (Singh and others, 2018).

The targets under Goal 5 address key barriers to gender equality such as discrimination (5.1), violence (5.2) and harmful practices (5.3), while promoting access to sexual and reproductive health (5.6), equal decision-making (5.5) and economic rights (5.a). In contrast, the focus of Goal 14 is on conserving marine ecosystems and resources, including by reducing pollution (14.1), mitigating ocean acidification (14.3) and restoring fish stocks (14.4). Fisheries are essential to ocean economies and community resilience. Notably, target 14.7 is focused on economic benefits from marine resources for small-scale fishers, which should explicitly support equitable access for women and other people in marginalized situations in the ocean economy (Silva and others, 2020).

Women's involvement in ocean conservation is often underrecognized, despite their unique perspectives and roles in sustainable marine practices (Gissi and others, 2018; Shellock and Maltby, 2023). However, limited representation of women in decision-making jeopardizes progress towards goals on sustainable ocean practices by reinforcing inequalities in resource access and policy influence (Baker-Médard, 2017). For instance, promoting sustainable fisheries requires gender-safe environments both on land and at sea, as well as policies that address the economic barriers faced by women and ensure equal access to markets and marine resources (Becker-Weinberg, 2019).

Empowering women in ocean-related sectors also requires investment in capacity-building, technological access and research opportunities (Fitrianggraeni, 2019; Mahabir-Lee and Rambarath-Parasram, 2019). Engaging women in ocean science bolsters innovation for sustainable marine resource management, especially as women play key roles in community-based conservation and climate resilience initiatives (Loarne-Lemaire and others, 2021; Gicheru and others, 2024). Women working in grass-roots organizations, for instance, often lead efforts to reduce marine pollution and educate communities, thereby transforming gender norms and improving urban coastal conditions (Hanson, 2017).

Lastly, increasing women's representation in international ocean conservation agreements is essential to fostering gender-responsive policies. Historically, ocean affairs have been male-dominated (Kitada and others, 2015), with slow but growing acknowledgement of women's roles. Expanding women's participation in ocean conservation and management, research, and policy development will not only advance Goal 5, but will also accelerate progress towards Goal 14, which is one of the Sustainable Development Goals with the lowest rates of implementation (Sachs and others, 2024; United Nations Department of Economic and Social Affairs (UNDESA), 2024). Gender-responsive ocean policies and inclusive decision-making processes will be key in moving towards a more equitable and sustainable ocean future.

3. Gender issues in ocean science

Overview of gender disparities in ocean science and governance

Gender equity in ocean science is not only an ethical imperative but also a means to improve the quality, relevance and impact of the science itself (Nielsen and others, 2017). As ocean sciences tackle increasingly urgent global challenges, the full participation of diverse talent is required for producing the best possible research and policy advice. While evidence of gender disparities in science has diminished considerably over time, women still have to contend with discrimination, unequal pay and difficulty accessing funding (Shen, 2013).

Gender disparities in representation across career stages reflect the persistent gender bias and multiple barriers that women face in ocean science (Giakoumi and others, 2021; Brooks and Déniz-González, 2021). In many areas, while gender balance has been achieved at the PhD student and recent graduate levels, women remain significantly underrepresented in higher-level academic and leadership positions. This pattern reflects the well-documented "leaky pipeline", a metaphor used to describe the underrepresentation of women at leadership levels of science and academia (Berryman and Rockefeller Foundation, New York, 1983; UNESCO, 2015).

Women face a range of gendered challenges in marine science workplaces, including harassment, stereotyping and unequal distribution of power, that require systemic, institutional and network changes in order to create conditions that allow a greater variety of leaders to advance to leadership roles (Shellock and others, 2022). Family-friendly institutional arrangements and gender-neutral parental leave can prevent mothers and fathers from being penalized in their science careers (Powell, 2021).

According to the best available data, women account for 38% of ocean researchers worldwide, with significant regional variations – from 4% in Mauritania to 62% in Croatia (Intergovernmental Oceanographic Commission (IOC-UNESCO), 2020). While the Global Ocean Science Report provides critical insights, data quality and reliability remain a challenge (Kitada and others, 2023; Ojwala, 2023). Johannesen (2024) highlights the lack of standardized, gender-disaggregated data, which makes global claims about gender representation difficult to validate.

Although women have substantial roles in marine conservation and governance, they are often excluded from decision-making (Ojwala and others, 2022). For instance, data from Kenyan ocean science institutions reveal that women hold just 25% of leadership roles in public universities, 17% in non-governmental organizations and 13% in government agencies (Ojwala, 2023). Gender equality is crucial to achieving the objectives of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), including through the integration of gender perspectives into ocean policies (IOC-UNESCO, 2020; Sun and others, 2021).

Challenges faced by women in fieldwork

Fieldwork in ocean science often demands extended periods in remote environments, posing unique challenges for women. Traditional male-biased workplace norms, caregiving obligations, safety concerns and physical demands related to ship design exacerbate these challenges (Johannesen and others, 2022). Sexual harassment remains pervasive, impacting women's professional and personal lives (St. Clair, 2021). Creating pathways to safe working environments is necessary to allow for greater inclusion of a broader range of social identities in ocean science (Amon and others, 2022).

Implicit biases also perpetuate inequalities, influencing hiring, funding and publication decisions (Calaza and others, 2021). For example, such biases create divides between knowledge systems, impeding collaborative efforts for ocean sustainability (Hägele and Hornidge, 2024). Addressing these biases is critical to fostering equity and inclusivity in the field (see subsect. 5B, chap. 5).

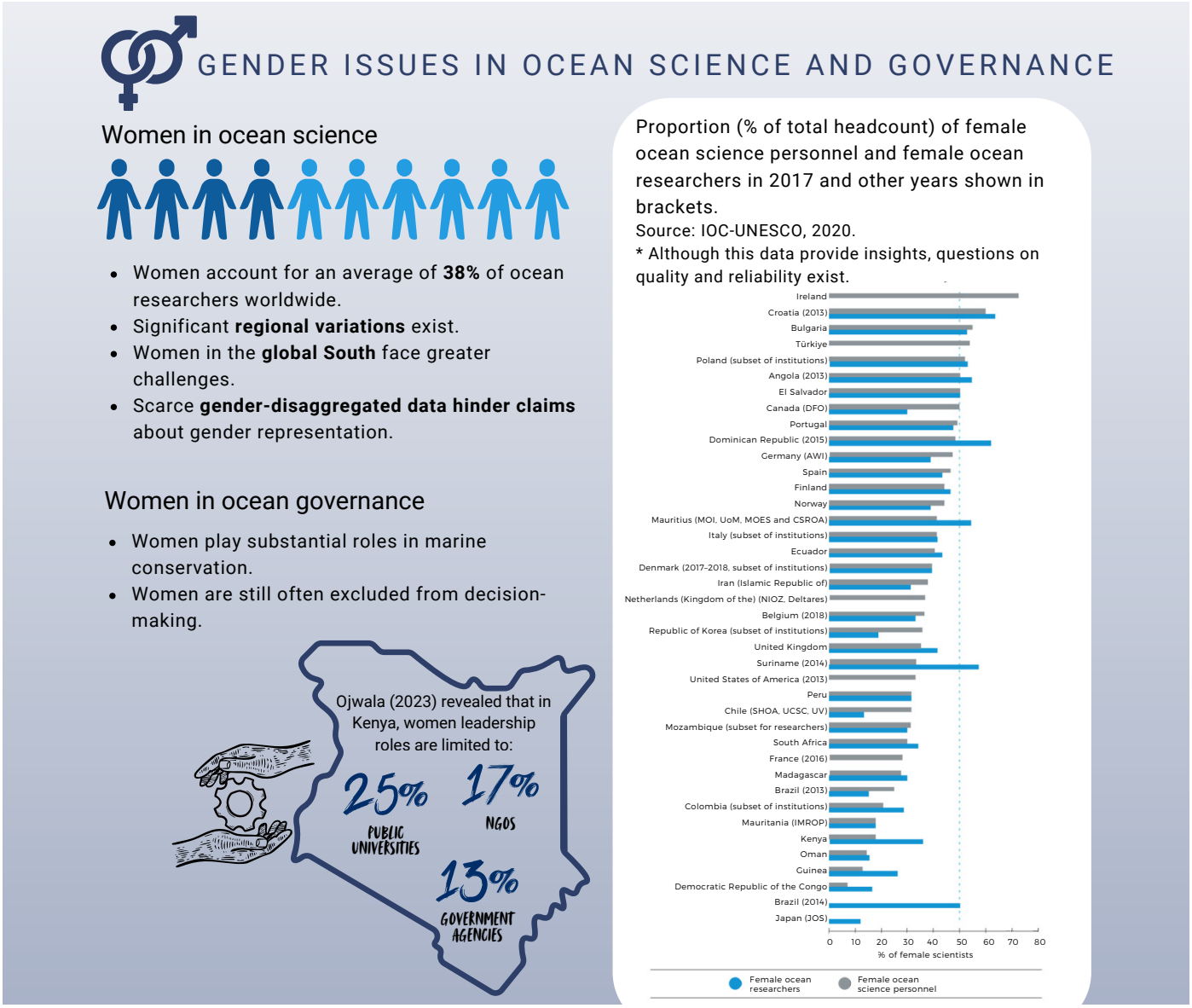
Initiatives and policies that promote gender equality in ocean science

Gender equality plans offer actionable steps for fostering inclusivity. In 2022, the European Union linked Horizon Europe research funding to gender equality plans, highlighting the importance of diversity in scientific teams. Similarly, through the "Empowering Women for the United Nations Decade of Ocean Science" programme, a high-level gender equality plan to guide organizations was produced (Sun and others, 2022; Rodríguez-Chaves and others, 2024). However, evidence from Kenyan ocean science institutions suggests that plans alone are insufficient: they must be systemically implemented (Ojwala and others, 2022; Johannesen, 2025).

Programmes such as Baltic Gender; Women in Ocean Science; "Empowering Women for the United Nations Decade of Ocean Science"; "Empowering Women in Hydrography" of the International Hydrographic Organization; and the International Seabed Authority (ISA) "S.H.E. See Her Exceed" mentoring programme are examples of regional and international efforts to enhance gender inclusivity. Mentorship programmes, representation in outreach initiatives and policies, such as conference quotas and leadership targets, contribute to fostering a more balanced ocean science community.

Gender-transformative policies not only promote equal rights for women and men in terms of employment, professional development and working conditions, but also ensure equal representation in leadership, decision-making and research teams. This, in turn, improves resilience and sustainability in ocean governance (Ojwala and others, 2022). In contrast, gender-neutral policies – often termed "gender-blind" – fail to advance true gender equality, as they are based on the assumption that women and men face the same challenges, and do not address the unique barriers that hinder inclusivity and equity.

Figure II
Gender issues in ocean science and governance



Source: Prepared by the writing team.

Integration of gender considerations into ocean science

Gender issues have increasingly been addressed in marine social science, highlighting power dynamics in sea-related practices. However, the focus has largely been on gender roles rather than on how dominant systems in science, policy and society are gendered (Pauwelussen and Lau, 2023). A systematic literature review reveals that marine social science largely treats gender as an object of study, with limited focus on researcher positionality and knowledge production. Expanding to gender-as-subject and gender-as-epistemology fosters intersectional, reflexive approaches. A gender-as-political-project perspective strengthens ocean equity by addressing structural inequalities, power dynamics and epistemological biases in marine research (Pauwelussen and Lau, 2023). Gender significantly influences access to and interaction with marine resources. In many regions of the global South, gender-specific restrictions, such as taboos and traditional practices, affect resource use and management (Jones and others, 2008; Oloko and others, 2024). Gender analysis is needed to improve coastal management and inform marine spatial planning (De la Torre-Castro and others, 2017). Inclusive management strategies enhance socioecological outcomes, uphold human rights and foster equitable governance systems (Bennett and others, 2021).

Challenges and opportunities in promoting gender equality

Promoting gender equity in traditionally male-dominated ocean science is essential for fostering diversity, innovation and human rights (Shellock and others, 2022). Despite their contributions, women in these fields continue to face systemic barriers, including underrepresentation, isolation, stereotyping and unsafe working environments (Shellock and others, 2022; Johannesen, 2025). For Black women and other women from minority groups, these challenges are further compounded by financial and structural obstacles that hinder their progress in ocean science programmes, from education to career advancement (Isma and others, 2023; Ojwala, 2024). High tuition costs, limited funding opportunities, limited access to career opportunities and wage disparities create significant roadblocks. A study by Isma and others (2023) revealed that over 60% of Black women in ocean science in the United States of America identified funding as a critical barrier to achieving their career goals. In addition, more than 40% of surveyed individuals had to take unpaid internships, while over 90% worked multiple jobs to support themselves due to lower wages for women. These financial constraints, combined with systemic discrimination and limited access to resources, create an uneven playing field that prevents talented individuals from fully participating in and contributing to ocean science.

Women also hold a mere 13–24% of senior leadership positions in European Union research institutions, with very few leading them. In publication, women account for only 18–22% of authors in top journals, with a significant gap in senior authorship. Funding data show a larger success rate for women in early grants, but their representation drops significantly in advanced funding stages (Giakoumi and others, 2021).

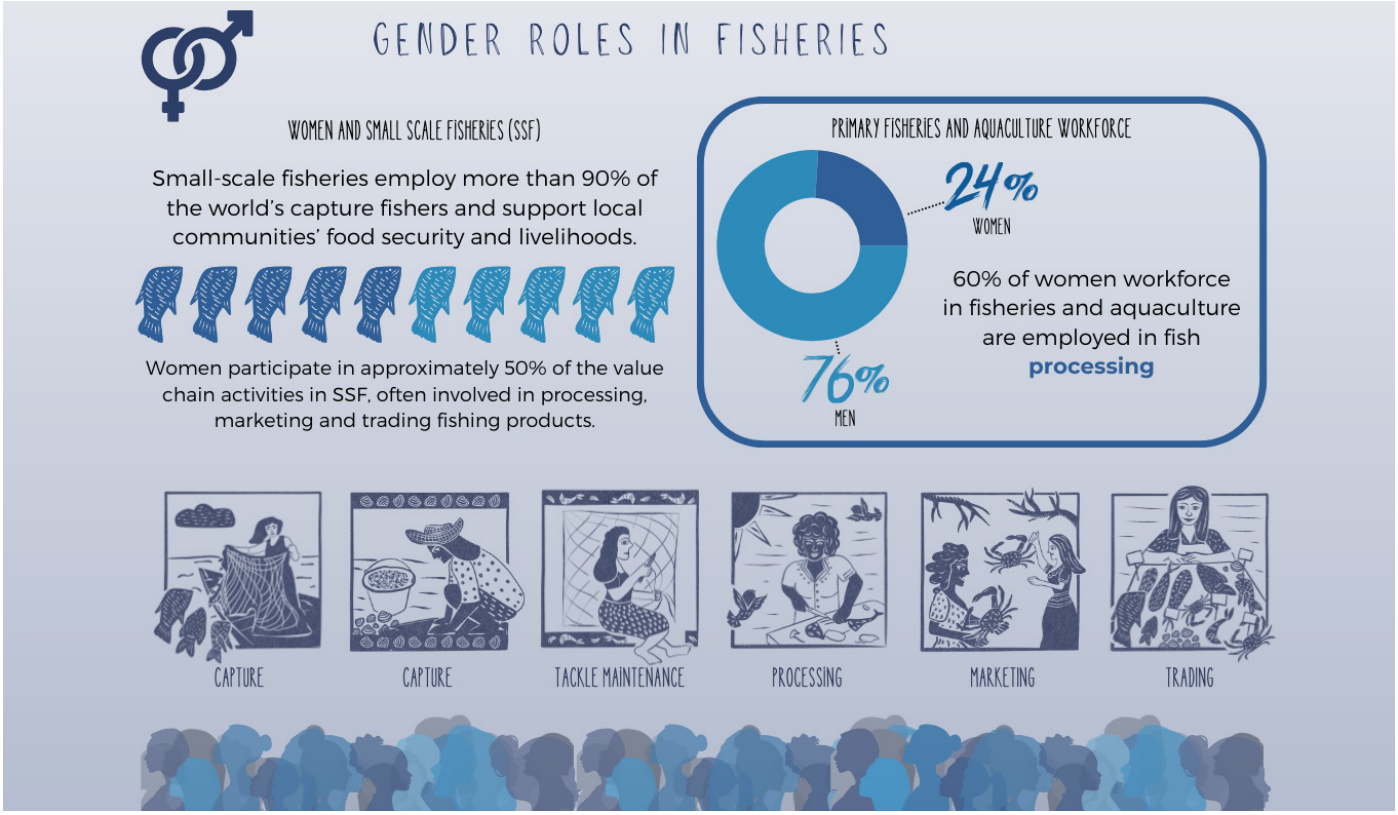
International actions, such as expanding funding opportunities, creating inclusive mentorship programmes and dismantling structural biases, are required to address these disparities and challenges. By breaking down these barriers, the ocean science community can harness the full potential of diverse perspectives, ultimately leading to more equitable and innovative solutions to marine challenges.

The absence of comprehensive gender-disaggregated data hampers efforts to assess and address disparities in ocean science education, employment and leadership (Ojwala, 2023; Johannesen and others, 2023). Such data are essential to understanding participation and contributions across genders, and provide insights into gaps in access to resources and career progression (Ojwala and others, 2022). Policymakers can use these insights to promote inclusivity and equitable governance, ensuring that ocean science efforts align with sustainability goals (Gissi and others, 2018). Addressing data gaps will enable more inclusive decision-making and support global progress in women's representation in ocean science and governance frameworks.

As the Ocean Decade neared its halfway mark, the Intergovernmental Oceanographic Commission of UNESCO initiated a process called Vision 2030 to refine the direction of future action under the Ocean Decade and further strengthen engagement and impact in the period up to 2030 and beyond. This process led to the identification of the need to "continue to enhance diversity, inclusivity, and equity in the Ocean Decade, and systematically identify and remove barriers to generational, geographic,

and gender diversity" (UNESCO-IOC, 2024). An Ocean Decade gender working group has been established to oversee development of a road map and action plan for enhancing gender equality in the Ocean Decade.

Figure III
Gender roles in fisheries



Source: Prepared by the writing team.

Note: This overview of gendered participation in fisheries highlights women's central roles in small-scale fisheries and along the value chain, particularly in processing, marketing and trading, alongside disparities in the primary fisheries and aquaculture workforce.

4. Incorporating a gender lens in fisheries and aquaculture

Overview of gender dynamics in fisheries and aquaculture

In 2022, approximately 62 million people were employed in the primary sectors of commercial fisheries and aquaculture, with women playing key roles across these "blue" food sectors by participating in organizations, administration, consulting and research (Food and Agriculture Organization of the United Nations (FAO), 2024; Frangoudes and others, 2020). These sectors are essential for nutrition, livelihoods and food security in rural coastal communities (Quimby and others, 2023; Thomas and others, 2021; Weeratunge and others, 2010). Women are active throughout fisheries and aquaculture value chains, particularly in processing, trading and marketing (Elias and others, 2024; Gopal and others, 2020). However, entrenched beliefs, norms and regulatory practices often define which activities are "feminized" or "masculinized", reinforcing a rigid gender division of labour (Kruijssen and others, 2018; Weeratunge and others, 2010). These dynamics highlight the fact that power, equity and equality within fisheries cannot be fully understood through a gender lens alone: intersecting social dimensions, such as age, class, ethnicity, ability and marital status, also shape women's roles and access to opportunities (McDougall and others, 2022).

Gender equality is imperative for diversifying seafood value chains and achieving "blue justice" within the sector (McClenachan and Moulton, 2022). However, women's contributions are often underrepresented in data, with limited gender-disaggregated information restricting

understanding of their participation (Merayo, Vakhitova and Carlson, 2024). This lack of documentation marginalizes women and slows the development of gender-sensitive policies in fisheries and aquaculture, perpetuating inequality (Szymkowiak and Rhodes-Reese, 2020; Kruijssen and others, 2018).

Representation and contributions of women in fisheries and aquaculture

Gender roles in fisheries and aquaculture differ globally, influenced by cultural, economic, political and ecological factors (Adam and others, 2024). Globally, women accounted for 24% of the primary fisheries and aquaculture workforce in 2022, with about 60% employed in fish processing (FAO, 2024). Women's roles are especially prominent in small-scale fisheries, where they participate in approximately 50% of value chain activities, often in roles related to processing, trading and marketing (FAO, Duke University and WorldFish, 2023; Weeratunge and others, 2010). In aquaculture, women's involvement in production, processing and marketing may surpass their involvement in that work in fisheries, contributing significantly to coastal community resilience (Kruijssen and others, 2018; Szaboova and others, 2022) (see also subsect. 5A, subchap. 1B).

Despite women's contributions in activities such as net-making, gear repair and bait acquisition, traditional definitions of "fishing" typically exclude these pre-harvest roles, meaning that women's labour and contributions are undervalued (FAO, Duke University and WorldFish, 2023). Men are more visible in data due to their engagement in offshore, boat-based fishing, while women's inshore activities, like gleaning for shellfish in intertidal zones, are less documented (Thomas and others, 2021; Weeratunge and others, 2010). This exclusion leads to an underestimation of fishing effort and catch volumes, affecting fisheries management decisions on local, national and international levels (Kleiber and others, 2015).

Challenges faced by women in fisheries and aquaculture

Women in fisheries face challenges that vary across sectors and regions but often include limited recognition, lower wages and unpaid labour (Elias and others, 2024). Women involved in processing in small-scale fisheries frequently receive lower or no pay, as their work is perceived as an extension of household duties, such as cooking and cleaning (Merayo, Vakhitova and Carlson, 2024). Meanwhile, men dominate more lucrative fishing sectors, resulting in stark income disparities (Cho, 2024). In aquaculture, women are often relegated to less profitable tasks and receive lower pay for the same work, hindered by traditional gender norms that limit their economic roles (Kruijssen and others, 2018; St. Louis and Oliveira, 2022).

Access to resources remains a significant barrier, with women facing challenges in securing financial support, owning property and participating in decision-making (Merayo, Vakhitova and Carlson, 2024). Limited access to financial instruments like loans prevents women from investing in essential equipment and land resources, further marginalizing them in fisheries and aquaculture (St. Louis and Oliveira, 2022). Traditional norms, such as those restricting asset inheritance or property ownership, also limit women's involvement and autonomy in these industries (Kruijssen and others, 2018) (see also subsect. 5A, subchap. 1C).

Gender-specific impacts of overfishing and environmental changes

Climate-driven changes to marine ecosystems pose severe challenges for aquatic food systems, especially in low- and middle-income coastal areas (Cochrane and others, 2023; Mitra and Barua, 2023). Climate change affects fish availability and trade, disrupts local food security and heightens coastal communities' vulnerability to extreme weather events, with women often disproportionately impacted (Nyasimi and Jakarasi, 2024; Barange and others, 2018). As fishing becomes increasingly dangerous, female fishers and processors, whose livelihoods depend heavily on fish harvests, are bearing the brunt of the economic consequences (Siles and others, 2019; Riviwanto and Basuki, 2019).

Gendered divisions of labour mean that men and women are exposed to different risks and stressors associated with climate change and overfishing. For example, when extreme weather prevents men from fishing, women who process and sell fish products may lose income sources, destabilizing entire households and communities (Shaffril and others, 2024; Almeida de Carvalho and others, 2023). Similarly, overexploitation of fish resources, particularly in shallow coastal waters (Ding and others, 2017), affects female workers primarily engaged in processing and trading (FAO, Duke University and WorldFish, 2023) for low-profit fisheries (McClanahan and Abunge, 2017), resulting in livelihood losses and an increase in

gendered food insecurity. Beyond economic hardship, unsustainable fisheries practices, such as overfishing, may also amplify the risk of sexual violence for female processors and traders (Nyasimi and Jakarasi, 2024).

Policies and initiatives promoting gender equality

Over the past decade, global fisheries policies have demonstrated increasing recognition of the role of women and contained a greater emphasis on gender equality (Mangubhai and Lawless, 2021). In its *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* (2015), FAO formally acknowledges the importance of gender mainstreaming for small-scale fisheries' development strategies. The Illuminating Hidden Harvests initiative (FAO, Duke University and WorldFish, 2023) supports the implementation of the *Guidelines*, and aims to close the gender data gap by highlighting both men's and women's contributions (see also subsect. 5A, subchap. 1B).

Despite these advances, fisheries policies often remain gender-blind in practice, with many practitioners lacking the training and knowledge necessary to implement gender-sensitive strategies (Mangubhai and others, 2022). Even in contexts with advanced fisheries policies, like Norway, the male-dominated ownership of fishing quotas underscores the need for additional gender-aware policies (Gerrard and Kleiber, 2019). Misunderstandings around gender equality also hinder implementation, as seen in Pacific tuna fisheries where perceived progress has not matched on-the-ground realities (Barclay and others, 2021).

In this context, mechanisms for scaling up successful gender-transformative initiatives and ensuring their integration into local governance frameworks would strengthen the link between policy and practice. Connecting female leadership to generational transition in this sector is essential.

Successful examples of integrating a gender lens in fisheries management

In many countries, women play a vital role in shellfish industries. For instance, in West Africa, women are integral to the harvesting, processing and marketing of shellfish in estuarine and mangrove ecosystems (Chuku and others, 2022). The oyster fishery in the Densu delta in Ghana has seen declining populations due to overfishing and habitat loss. In response, the United States Agency for International Development, through its Sustainable Fisheries Management Project, partnered with the Development Action Association and the Ghana Fisheries Commission to address the issue by establishing the Densu Estuary Women's Oyster Pickers Association (Agbekpornu and others, 2021; Torell and others, 2019).

The approximately 200 members of the Association work to restore oyster habitats and implement sustainable management practices. These women have increased their skills with training in leadership, oyster ecology and water quality monitoring, meaning that they are able to contribute to a more sustainable fishery (Chuku and others, 2022). The project's peer-to-peer learning programmes have fostered greater confidence among participants, allowing the Association's model to serve as a scalable example of community-driven, women-led fisheries co-management (Agbekpornu and others, 2021).

The Association demonstrates how women's contributions to resource management can be harnessed for effective fisheries governance. By empowering fisherwomen in Ghana, the programme has strengthened their roles as stewards of local biodiversity while promoting sustainable livelihoods. Initiatives like this one underscore the potential for similar models in other regions, where empowering women through training, leadership development and community-based management can enhance the sustainability of fisheries and aquaculture (Torell and others, 2019; Crawford and others, 2022).

5. Incorporating a gender lens in the maritime industry

The maritime industry is a capital-intensive business that serves as an economic backbone for many countries. The industry involves heavy ship and port infrastructure, where women are underrepresented. Of 1.9 million seafarers worldwide, women seafarers are estimated to account for only 1.28% (Baltic and International Maritime Council and International Chamber of Shipping (BIMCO and ICS), 2021). In ports, women occupy management or administrative positions, but they comprise only 17% of the overall port workforce, according to the United Nations Conference on Trade and Development (UNCTAD) (2022), which investigated 58 port entities in 2021. In the same year, a survey conducted by the International Maritime Organization (IMO) and the Women's

International Shipping and Trading Association (WISTA) revealed that 39% of women who worked in companies were in mid-management, 28% were in technical roles and 48% were in administrative and support roles. Women made up around 20% of the workforce in maritime authorities (IMO and WISTA, 2021) (see also subsect. 5A, chap. 6).

Generally, the maritime industry is characterized by both horizontal and vertical gender segregation, which makes it hard to attract and retain women (Kitada, 2022; IMO and WISTA, 2021). Traditionally masculine attributes, such as physical strength, technical and engineering experience, and certain leadership styles are also valued in the work culture. That culture is also seen in maritime education, and fewer women take maritime-related courses, especially technical and engineering subjects. In Europe, approximately 13.5% of students enrolled in nautical courses are women, and an average of 6.3% of marine engineering students are women (Barahona-Fuentes and others, 2020). While women seafarers have historically been disadvantaged in terms of finding employment and accessing on-board practical training, recent initiatives have the potential to address these inequalities, leading to a gradual increase in their participation in the sector (World Maritime University (WMU), 2023).

Recently, there has been awareness-raising in the maritime industry, which has made it possible to discuss gender and diversity in relation to well-being and occupational safety and health. Inspired by the World Maritime Day theme for 2019, "Empowering women in the maritime community", the States members of IMO adopted resolution A.1147, entitled "Preserving the legacy of the world maritime theme for 2019 and achieving a barrier-free working environment for women in the maritime sector", in December 2019 (IMO, 2019). In response to a number of reported and unreported cases of sexual harassment and bullying of female crew members (Carballo Piñeiro and Kitada, 2020), in February 2024 the International Labour Organization (ILO) and IMO convened the Joint ILO/IMO Tripartite Working Group to identify and address seafarers' issues, with a focus on violence and harassment, including sexual harassment, bullying and sexual assault (IMO and ILO, 2024). There is an urgent need for the maritime industry to ensure a safe working environment. One of the solutions under discussion at IMO is to make training on violence and harassment, as well as psychological safety, mandatory under the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers. Several States members of IMO have also stressed the importance of incorporating the perspectives of other gender minorities, such as lesbian, gay, bisexual, transgender, intersex and queer persons, into the design of a safe working environment at sea (IMO, 2023) (see also subsect. 5A, chap. 6).

In addition to the human dimension of gender equality, the concept of gender equality has recently become a factor in a just and equitable transition in the maritime industry. In 2022, the Maritime Just Transition Task Force was established by United Nations agencies and industry stakeholders with the aim of promoting smarter and greener shipping in a just and equitable manner (Maritime Just Transition Task Force, 2022). Today, gender equality is recognized as the top priority in the industry, although there is still a long way to go to remove all the barriers to women and people with diverse gender identities in order to achieve diversity and inclusion in the industry (see also subsect. 5A, chaps. 6 and 7).

6. Strengthening science-based approaches

Integrating gender perspectives into science-based marine solutions makes practices more equitable and enhances innovation, participation and sustainability (Alexander and others, 2022). Several successful initiatives demonstrate how gender-transformative approaches lead to improved research outcomes, reduce inequalities and strengthen community resilience.

For instance, the Gendered Innovations project of Stanford University highlights case studies that showcase how gender perspectives have contributed to improved outcomes in marine research. Studies included designing gender-sensitive equipment that enables both men and women to participate effectively in marine fieldwork and developing policies that address gender disparities in research funding and opportunities (Johannesen and others, 2022). Such examples illustrate that when technology and innovation are designed to be inclusive, they not only accommodate a broader range of users, but also enhance research quality and engagement.

In the Baltic region, Baltic Gender has pioneered the GenderWave tool, which supports the incorporation of gender perspectives into marine research and innovation. This

tool supports research institutions in analysing and addressing gender imbalances across scientific disciplines and organizational structures (Baltic Gender, 2020). By fostering gender-aware practices in research, the GenderWave tool promotes a more equitable research environment and sets a model for other regions seeking to balance gender representation in science.

Collaboration between researchers, policymakers and local communities is essential to addressing gender disparities in ocean-related activities. Effective partnerships amplify marginalized voices, especially those of women in the fishing and extractive industries, thereby ensuring that policies reflect the diverse experiences and needs of those communities.

A notable example is the network of women from extractive and fishing communities in southern Bahia, Brazil. In a region heavily impacted by environmental degradation, predatory fishing and real estate pressures, local communities mobilized to protect their livelihoods through the Canavieiras Extractive Reserve, established in 2006 (Carmo and others, 2016). Recognizing the male dominance in the management of the Reserve, women fishers and shellfish gatherers formed the network of women from extractive and fishing communities in southern Bahia in 2009 (Ettinger, 2013; Figueiredo, 2015).

The network aims to empower women, promote gender equity and advocate policies that address women's unique challenges in extractive activities. Through it, women have gained the skills and confidence to participate actively in management discussions, advocate for their rights and take on leadership roles within their communities (Ettinger and others, 2016). Training sessions and forums organized by the network cover a range of topics, from technical skills to economic autonomy and legal rights, allowing women to build capacities that extend beyond their work in extractive industries (Ettinger, 2013; Carmo and others, 2016).

The network's impact is multifaceted: not only has it enhanced women's economic empowerment, but it has also fostered a sustainable management approach that aligns local traditions with environmental preservation. By engaging in sustainable fishing practices and educating communities on ecosystem protection, the network has contributed to safeguarding biodiversity and promoting long-term food security (Figueiredo, 2015). This community-driven model exemplifies how collective action rooted in gender equality can drive social, economic and environmental change.

In fisheries and aquaculture, access to gender-transformative technology has empowered women to participate in new ways. A powerful example of this is in the seaweed farming sector in Zanzibar, United Republic of Tanzania. Initially introduced as a means of economic empowerment for women, seaweed farming in Zanzibar has faced challenges, including declining productivity due to climate change and insufficient access to appropriate technology. In response, through the SeaPoWer project, tubular net technology for seaweed farming has been introduced, enabling women to shift their operations to deeper waters. This helps to mitigate climate-related declines in coastal yields, enabling more sustainable cultivation (Brugere and others, 2020). This initiative has not only provided women with essential skills in boat handling and environmental monitoring, but also created pathways for women's leadership in aquaculture innovation (Brugere and others, 2019; Gopal and others, 2020). Gender-sensitive technological interventions like these transform blue economy sectors by enhancing productivity, expanding livelihood opportunities and creating a more inclusive industry (see also subsect. 5A, chap. 6).

Gender-transformative technology is essential to advancing ocean science by ensuring that innovations are accessible, equitable and beneficial to people of all genders involved in marine research, management and conservation. Integrating gender perspectives into technology development entails consideration of the specific needs, experiences and constraints of women and other marginalized people, and thus promotes greater inclusivity, participation and innovation. For instance, area-based management tools like the Western Indian Ocean Symphony support ecosystem-based marine spatial planning, providing data-driven solutions that respond to diverse stakeholder needs (Nairobi Convention and Swedish Agency for Marine and Water Management (SwAM), 2021). Such gender-responsive technologies are needed to empower a wider range of users and to enhance the contributions of women to ocean scientific research and governance.

Incorporating gender perspectives into science-based approaches for ocean-related sectors like fisheries, aquaculture and marine conservation leads to more inclusive, sustainable and effective outcomes (see also subsect. 5A, subchap. 1C). Success stories from projects like SeaPoWer in Zanzibar and the women's network in southern Bahia demonstrate how gender-sensitive initiatives empower women, enhance resource sustainability

and promote community resilience. Collaborative efforts between researchers, policymakers and communities are essential to addressing gender disparities in ocean sectors and implementing meaningful change. The integration of gender into ocean science makes it possible to adopt a more inclusive and resilient approach to marine conservation that is capable of addressing the diverse challenges of a rapidly changing world.

Ultimately, gender-transformative strategies in science-based solutions pave the way for sustainable development in marine and coastal environments. Gender equity must be central to our efforts, in the light of the invaluable roles that women play in marine stewardship and community resilience. By fostering innovation, collaboration and gender-sensitive policies, we can work towards a future where marine resources are managed sustainably and equitably for the benefit of all (see also subsect. 5B, chap. 5).

7. Conclusion

In the present chapter, the role of gender equality in ocean science and governance has been explored, and the ways in which a gender perspective can enhance the effectiveness, inclusivity and sustainability of ocean-related activities have been highlighted. Important strides in addressing gender disparities, including the Sustainable Development Goals and recent international agreements, such as the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, were emphasized. A gender lens allows for a more holistic view of marine sectors and the acknowledgement of the unique contributions of women, especially in fisheries, aquaculture, climate adaptation and marine conservation.

Gender disparities remain significant in these fields, with barriers for women ranging from limited access to leadership positions to systemic biases that result in the undervaluation of their roles and contributions. Women's roles in marine and coastal communities, often in areas like processing, trading and local conservation, underscore women's importance in the socioecological resilience of those communities. However, persistent structural challenges limit their involvement in decision-making and leadership. Studies reveal that gender-diverse teams and inclusive governance structures bring a broader range of perspectives and more innovative solutions to marine conservation and governance challenges. Initiatives like the Gendered Innovations project and the Baltic Gender project, and local efforts, including the SeaPoWer project in Zanzibar and the network of women from extractive and fishing communities in southern Bahia, illustrate how gender-transformative approaches can lead to more sustainable and impactful marine management and conservation practices.

Promoting gender equality in ocean science and governance is not merely an ethical imperative: it is essential for effective and adaptive marine resource management. As has been demonstrated in the present chapter, fostering inclusivity through gender-sensitive policies, training and research contributes to healthier marine ecosystems and more resilient coastal communities. Integrating women's knowledge and leadership into ocean science makes it possible to address pressing environmental issues with greater nuance and cultural awareness.

A call to action, aimed at expanding and deepening gender equality efforts across ocean-related sectors, is therefore warranted. First, governments and international organizations must prioritize gender equality in policy frameworks and integrate gender-focused objectives into marine conservation and resource management initiatives. Also, funding bodies should provide targeted resources to support gender-sensitive research and training, particularly in regions where gender disparities are most pronounced.

Ocean governance institutions can play a pivotal role by establishing leadership programmes and mentorship opportunities for women, particularly those from underrepresented backgrounds, including women of colour, Indigenous women, and lesbian, gay, bisexual, transgender, intersex and queer individuals. Gender-disaggregated data collection must also be prioritized, as data gaps remain a major barrier to the visibility of gender inequalities in these fields, and to accurate assessments and responses. Increasing awareness through gender training, as seen in projects like the "Empowering Women" initiative under the United Nations Ocean Decade, can help to dismantle biases and foster a culture of inclusion and respect in ocean science.

As the field of ocean science and governance continues to evolve, future research must focus on several key areas to ensure that gender equality is fully integrated

into marine resource management. One potential area is the intersectionality of gender and other social factors, such as ethnicity, class and geography. Future studies can investigate how these intersections affect women's access to resources, decision-making power and roles in marine sectors, allowing for a more nuanced understanding of the barriers and opportunities within these industries.

Another critical direction is the development and assessment of gender-sensitive technology in marine science. Technological innovations, particularly in remote sensing, marine biology and climate monitoring, can benefit from inclusive design principles that make them accessible and relevant to diverse user groups. Researchers can explore how such technology may empower women in ocean-related fields, particularly by reducing physical barriers in activities like data collection and fieldwork.

The impacts of climate change on gender disparities in ocean science and coastal management are also worthy of further study. As climate-induced shifts affect fishery resources, coastal habitats and marine biodiversity, an understanding of the gender-specific impacts on livelihoods and resilience can guide the formulation of adaptive policies that support both ecological and social resilience. In addition, future research could be focused on how women in local communities are adapting to climate pressures through community-led conservation initiatives and sustainable resource management, which could provide valuable insights for scaling these practices globally.

Lastly, expanding research into the economic contributions of women in fisheries, aquaculture and conservation can bring visibility to their roles and contributions. Quantifying these economic impacts would help to correct the long-standing undervaluation of women's labour and encourage policymakers to allocate resources to and support programmes that enhance women's economic empowerment in marine sectors (see also subsect. 5A, subchap. 1C).

Promoting gender equality in ocean science and governance is integral to creating more sustainable, resilient and equitable marine ecosystems. Acknowledging and addressing gender disparities enables more effective and inclusive stewardship of marine resources. As the present chapter has shown, diverse voices and perspectives enrich conservation and governance practices, making them more adaptable and better suited to meet the challenges of a changing world.

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Chapter 7
Pandemics, including impacts of the coronavirus disease pandemic

Key points

- The coronavirus disease (COVID-19) pandemic affected marine ecosystems and the people who depend on them all around the world.
- Seafood workers were particularly susceptible to contracting the disease, as a result of particular working conditions.
- Lockdowns and other public health measures caused immediate drops in seafood demand and tourism worldwide.
- Decreases in boat traffic and visitors to popular tourist destinations resulted in several sightings of species in places where they are rarely seen, or in higher densities compared with the years before the pandemic.
- Cancelled scientific surveys and decreases in fisheries observations resulted in an increase in illegal fishing activities in some areas.
- There are still many unknowns in terms of the direct and indirect effects of the COVID-19 pandemic; more research is needed to prepare for future human pandemics.

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1. Introduction

Human pandemics are rare events that can have outsized impacts on marine ecosystems (Bennett and others, 2020; Food and Agriculture Organization of the United Nations (FAO), 2020; Ross and others, 2021; White and others, 2021). In 2020, the COVID-19 pandemic started to spread around the globe. In 2020 and 2021 alone, there were over 10 million excess deaths related to the disease (World Health Organization, 2022). The pandemic had both immediate and long-lasting impacts on marine ecosystems and those who rely on them, as well as direct health and safety implications for those working in the seafood sector and in coastal areas (FAO, 2020; Sorensen and others, 2020). For example, studies show that seafood workers were particularly susceptible to being infected by COVID-19, as a consequence of tight working quarters and moist working conditions (White and others, 2022) – not because they were handling seafood, as the COVID-19 pandemic was sustained through human-to-human transmission (FAO, 2021). In addition, because of the mandatory use of personal protective equipment, such as face masks and gloves, plastic use, and consequently plastic pollution, increased in the early phases of the pandemic, especially before vaccines became widely available (Aragaw, 2020; Chen and others, 2021). Neither health and safety issues affecting seafood workers, nor plastic pollution, is new or unique to the pandemic, but the event did intensify those and other ongoing problems, such as the marginalization of groups that are especially vulnerable to the impacts of COVID-19.

In addition to those direct impacts, a host of secondary effects developed as lockdowns and other public health measures were put into place (White and Hébert-Dufresne, 2020). This period has been termed the "anthropause" due to the resulting decrease in anthropogenic activity across both terrestrial and marine ecosystems (Rutz and others, 2020). For example, mobility restrictions affected businesses in coastal areas. In view of the drastic decline in people eating in seafood restaurants and engaging in tourism in coastal areas, workers in those areas were hit particularly hard (see figure) (Bennett and others, 2020; Love and others, 2021; Ward-Paige and others, 2020; White and others, 2021). In areas that are highly dependent on tourism (see subsect. 5A, chap. 4), livelihoods completely shifted during the pandemic (Abbas and others, 2021). For example, in the Galápagos Islands, essentially all tourism stopped early in the pandemic (Díaz-Sánchez and Obaco, 2021). In the European Union and other regions that are highly dependent on fishing activities, some businesses began selling seafood directly to consumers (Villasante and others, 2021, 2024). The pandemic also had lingering effects on ocean and coastal communities. For instance, consumer preferences shifted, as people began cooking more seafood at home, a trend that continued after the pandemic (Stoll and others, 2021; Villasante and others, 2024).

Taken all together, pandemic-related restrictions affected a substantial population. Over 750 million people, because of where they live, depend heavily on marine resources (Selig and others, 2019), while in the United States of America alone, 3 million people work in ocean-dependent businesses (National Oceanic and Atmospheric Administration (NOAA), 2024). Furthermore, aquatic foods provide at least 20% of the animal protein intake of 3.3 billion people across the globe (FAO, 2022). The COVID-19 pandemic also revealed the importance of community organizations in the provision of social security support, particularly during idiosyncratic shocks (FAO, 2022).

At the same time, some animal species may have benefited from the reduced human presence, including decreases in tourism and boat traffic (Thomson and Barclay, 2020). Throughout the pandemic, species, including marine megafauna, were reported inhabiting waters where they had rarely been seen in the years prior to the event (Rutz and others, 2020). In addition, the corresponding reduction in underwater noise led to changes in the communication behaviour of some animals (Laute and others, 2022).

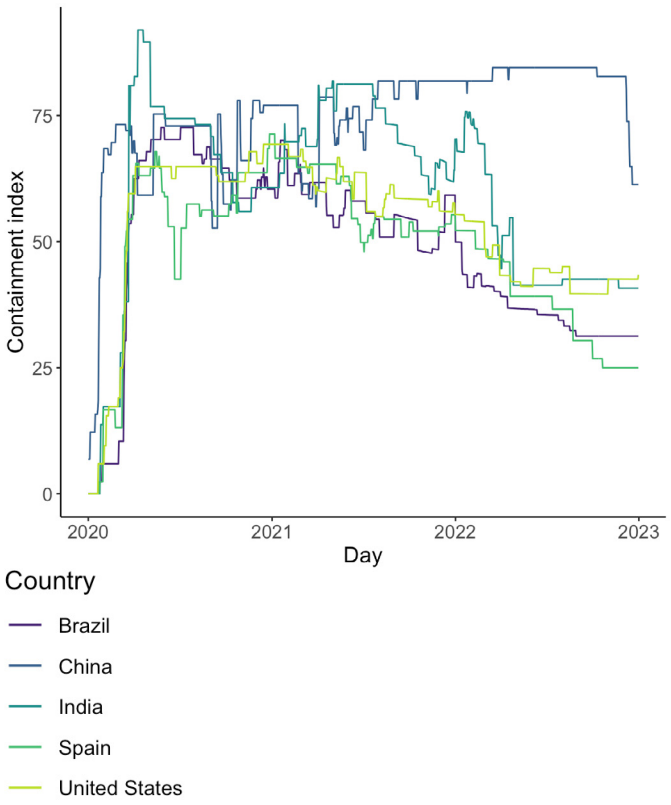
While the COVID-19 pandemic had wide-ranging effects, it is not the first human pandemic to have affected the world's oceans. The flu pandemic of 1918–1920 killed more than 50 million people worldwide (Martini and others, 2019). The disease spread quickly, especially as the First World War raged on, causing people to move across the globe. Similar to during the COVID-19 pandemic, many non-pharmaceutical measures, such as social distancing, went into effect during the flu pandemic of 1918–1920. Because of strong mobility restrictions, some Pacific islands, including American Samoa, remained relatively unscathed by the pandemic (Shanks and Brundage, 2013). However, coastal communities, including Inuit groups across the Arctic, were hit particularly hard (Mamelund and others, 2013). In those communities, workers were concentrated during short fishing windows in the summer

(Paskoff and Sattenspiel, 2019). Fishing pressures in many places around the globe also decreased at that time, but this was primarily due to fishing boats being used for wartime activities. Elsewhere, such as in eastern Canada, there were no changes in catch during the pandemic (Schijns and others, 2021). Similarly, the outbreak of severe acute respiratory syndrome (SARS) in 2003, which had nearly a 10% mortality rate, impacted local and regional economies (LeDuc and Barry, 2004). In particular, the growth rate of Chinese ocean-related industries declined drastically during that period, much faster than the Chinese economy as a whole (Zhao and others, 2014).

Despite these previous pandemics, the unprecedented nature of the COVID-19 pandemic, along with its associated lockdowns, meant that early in the pandemic there were gaps in terms of knowledge, policies and the capacity to emerge. For example, new policies had to be written to ensure the safety of workers in the seafood sector and to distribute relief funds to them in some locations (European Commission, 2020). Early in the pandemic, the leaders of National Oceanic and Atmospheric Administration fisheries compiled their thoughts on how science and management might have to change for future pandemics, including as a result of travel restrictions (Link and others, 2021). In addition, data and monitoring gaps occurred in many places during the pandemic. The pandemic created challenges and opportunities, with heterogeneous impacts that varied according to the scale of seafood operations, production methods, geography, value chains and gender (Love and others, 2024). The cumulative impacts of climate change and conflicts also contributed to pandemic-related hardships.

The present chapter provides a review of the literature, covering the period from 2020 to 2024, on the various ways in which the COVID-19 pandemic impacted coastal communities and marine ecosystems. In addition to highlighting effects specific to human pandemics, it illustrates how the pandemic aggravated existing issues, such as plastic pollution. Persisting knowledge gaps are noted, and ways that future pandemics could be handled to take marine ecosystems into consideration are discussed. References are made to other chapters in the third *World Ocean Assessment* that are intricately linked to the COVID-19 pandemic.

Figure
Containment of the COVID-19 pandemic in five countries



Source: Hale and others, 2021.

Note: Composite measure of containment based on 13 policy response indicators, including school closures, workplace closures, travel bans, testing policies, contact tracing, face coverings and vaccine policies, rescaled to a value from 0 to 100 (100 being the strictest).

2. Impacts of increase in single-use face mask use in the context of pollution

To slow down COVID-19 transmission, people had to use personal protective equipment, such as face masks, goggles and gloves, most of which were single-use. The use of single-use face masks was mandatory and common during the pandemic, as they are considered an effective and affordable public healthcare measure for containing viral transmission. For instance, on fishing vessels departing from ports in Namibia, fisheries observers and fishing crews were expected to consistently wear face masks while on board (Erasmus and others, 2022).

However, the marked increase in the manufacture and use of plastics throughout the pandemic led to a significant increase in the illegal disposal of plastic waste into

the oceans globally (Shams and others, 2021; Williams and Rangel-Buitrago, 2022). In particular, the mismanagement of face masks and other personal protective equipment has caused various problems (Mallik and others, 2022; Wang and others, 2023); an estimated 10 million face masks could have been improperly disposed of and introduced into the environment monthly during the pandemic (World Wide Fund for Nature (WWF), 2020).

Not only do single-use face masks and other personal protective equipment reduce the aesthetic and recreational value of the environment (see sect. 4, subchap. 6E), as seen on Italian beaches (Saliu and others, 2021), but they can also easily be ingested by fishes and other organisms, creating an ecological problem (Chen and others, 2021; Jimoh and others, 2023). In addition, wild animals have become entangled in face masks, which can cause immediate mortality or reduce feeding, facilitate predation, and cause infection or wounds, among other effects (Patrício Silva and others, 2021). Face masks are also a source of microplastics as they contain polystyrene, polypropylene, polyester or polyethylene (Aragaw, 2020; Chen and others, 2021). It is well known that microplastic pollution can inhibit the growth rates, feeding and reproduction of marine species, while also causing stress, neurotoxicity and even death (Jimoh and others, 2023).

3. Impact of lockdowns and human activities in the ocean on animal behaviour, biodiversity and presence

The reduction of human presence on and near the ocean, which included less marine shipping traffic, recreational activities and fishing, changed the behaviour of a variety of marine species. These changes were mostly positive and included enhanced communication and breeding success, reoccupation of urbanized areas, or increases in biodiversity and abundance (Abbas and others, 2021). However, the reduced human presence also had neutral or negative effects on some species, including owing to increased illegal activities and less conservation and other forms of human assistance (Fournet and others, 2021; Pine and others, 2021).

One of the major effects of the pandemic on the ocean was the reduction of shipping and other anthropogenic activities, which in turn decreased noise pollution. Ambient sound pressure levels were significantly lower in many regions, sometimes even three times quieter (Fournet and others, 2021; Pine and others, 2021). Below 100 Hz, the frequency range often dominated by shipping sound, an average reduction of 1.5 decibels was reported in Vancouver, Canada, during the first quarter of 2020 compared with the previous year (Thomson and Barclay, 2020). In other regions, ambient sound pressure levels did not vary significantly, especially if the soundscape was commonly dominated by other sources of sound, like biological sounds (e.g. humpback whale songs (Madrigal and others, 2024)) or geophonic sounds (naturally occurring non-biological sounds (Laute and others, 2022)).

Since sound travels quickly and far underwater, marine species often use sound for various life functions, including communication (see sect. 4, subchap. 4E). The reduction in noise pollution in many ocean regions led to a change in the communication behaviour of some acoustically active species, including increases in call rate, type or intensity (Duane and others, 2023; Fournet and others, 2021). For instance, a doubling in the number of humpback whale calls (Laute and others, 2022) and an increase in white-beaked dolphin whistles (Reverberi, 2023) were recorded in Iceland when there were fewer whale-watching vessels. In New Zealand, the communication range of fish and dolphins increased by an estimated 65% (Pine and others, 2021).

In addition, the reduced number of visitors on shorelines impacted the breeding and nesting behaviour of some species. For instance, sea turtle nesting behaviour improved, with an increased number of nests and more nesting time in various places, including Costa Rica, India, Thailand and the United States (Loh and others, 2022; Quesada-Rodríguez and others, 2021). In contrast, a breeding colony of common murres was disturbed by a sevenfold increase in the number of sea eagles, attributed to the absence of tourists (Hentati-Sundberg and others, 2021). Furthermore, the reduced human presence in coastal areas, along with improved visibility due to clearer water (Saadat and others, 2020), led to various sightings of animals in uncommon habitats. Similar to reports of wildlife in deserted cities, examples of unusual marine sightings include dolphins in the harbour of Trieste, Italy (Rutz and others, 2020), eagle rays in Dubai Marina (Bar, 2021), dugongs and false killer whales close to the coast in Thailand (Usui and others, 2021) and sea lions in urban centres in Argentina (Usui and others, 2021). Many studies also reported increased biodiversity, including in coral reefs (China and others, 2021; Patterson

Edward and others, 2021; Somchuea and others, 2022) and mangroves (Chaudhuri and Bhattacharyya, 2021). The reduced presence of humans, along with less fishing and harvesting, also resulted in higher abundances of fish (Bertucci and others, 2023; Feeney and others, 2022; Johnson and others, 2023; Kough and others, 2022; Lecchini and others, 2021; Olán-González and others, 2022, 2023; Patterson Edward and others, 2021; Somchuea and others, 2022; Weng and others, 2023; Yosef and others, 2022), shrimp (Coll and others, 2021) and horseshoe crabs (Degnarain, 2020). (These increases were likely a result of short-term changes in habitat use rather than increases in the total population size.) However, some negative impacts on marine ecosystems were also reported after the COVID-19 pandemic. For instance, some fish populations may have been exposed to an increase in unregulated fishing activities (Mallik and others, 2022), and the SARS-CoV-2 virus may have directly affected marine species, due to its potential to infect marine mammals and birds (Mohapatra and others, 2021). Birds and marine mammals such as whales, seals and dolphins can be infected by different coronavirus genera, which they could have come into contact with through discarded medical waste in the water. In the past, dozens to thousands of harbour, Baikal and common seals, striped dolphins and harbour porpoises have died of viral pneumonia or measles (Mohapatra and others, 2021).

4. Changes in shipping and port activities and impacts on seafarers and port workers

Facilitating the maritime supply chain was critical during the pandemic. The unprecedented impacts on global trade flows meant that the maritime supply chain, in particular, shipping and port activities, needed to adapt to changes rapidly (United Nations, 2021). Each stage of the fisheries and aquaculture supply chain was susceptible to being disrupted or stopped by measures arising from COVID-19 restrictions. Only by protecting each stage of the supply chain could the continued availability of fish and fish products be ensured (FAO, 2021). Ports are key infrastructure that support international trade and the global economy, and port workers and seafarers are vital actors in the maritime supply chain. According to the International Labour Organization (ILO), there are over 2,000 ports globally, including 856 international ports, with variable sizes, services and capabilities (United Nations, 2021). In its resolution 75/17, the General Assembly recognized that there were approximately 2 million seafarers serving over 98,000 commercial ships, transporting more than 11 billion tons of seaborne trade in 2019 (United Nations, 2020).

Lockdowns and movement restrictions limited the ability and functioning of seafarers and port workers, which adversely impacted the maritime supply chain. According to the International Maritime Organization (IMO), the impacts of the COVID-19 pandemic on seafarers and other maritime professionals included isolated crews, difficulties in repatriation, altered working conditions and labour shortages. For instance, there were significant challenges in terms of crew change and seafarers' welfare conditions, including their rights to wages, shore leave, sick leave, access to medical care, food supplies and repatriation (United Nations, 2020). Many seafarers and port workers were stuck on-board ships for months beyond the end of their contracts due to travel restrictions and the lack of clear protocols for crew replacement. IMO estimated that, in 2020, around 400,000 seafarers globally had not been repatriated and were still on their ships despite their contracts having expired, while another 400,000 were unable to join ships and provide for their families (Gautham, 2021; IMO, 2022).

In addition, in some places, such as Spain, shortages of port workers due to infections or quarantines resulted in slower port operations and increased delays in loading and unloading ships. Another drawback was the lack of inspectors and administrative staff to renew fishing licences in other countries due to restrictions. Fishers were also impacted. For example, in Galicia, Spain, the mental and physical health of fishers was also affected after the first lockdown, which began in March 2020. They were scared of the virus due to the lack of space on board for social distancing among crew members, the scarcity of sanitary material for fishers and the need to protect family members (Villasante and others, 2021).

Travel restrictions and lockdowns from COVID-19 significantly disrupted port operations and, consequently, international trade and commerce. While trade declined globally, impacts varied regionally. For instance, major drops occurred in ship calls in Europe, Oceania and the Americas, while moderate decreases occurred in Africa, the Far East and the Persian Gulf (United Nations

Conference on Trade and Development (UNCTAD), 2022b). UNCTAD reported an 8.7% contraction in ship calls globally in the first half of 2020 compared with a year earlier (UNCTAD, 2022b).

To ease trade, it was necessary to ensure swift and safe cargo handling in the maritime supply chain, which entailed regulatory, governance and operational adjustments for ports, port workers and seafarers. Port workers and seafarers were given the status of "essential workers" or "key workers" in various countries (UNCTAD, 2022b). However, the severity of the measures varied by country (UNCTAD, 2022b). In 2020, the General Assembly adopted resolution 75/17, urging Member States to designate seafarers and other maritime personnel as "key workers" (United Nations, 2020). In that resolution, the Assembly also encouraged the implementation of the travel and ship crew change protocols approved by the IMO Maritime Safety Committee at its 102nd session, in order to ensure safety during the COVID-19 pandemic. This protection was further bolstered by the resolution adopted by the IMO Assembly at its thirty-second session, in which the Assembly urged member States to designate seafarers as "key workers" to "facilitate shore leave and safe and unhindered movement across borders", to prioritize the vaccination of seafarers and to provide them with immediate access to medical care and medical evacuation in cases where urgent medical attention was required (IMO, 2022).

IMO, in coordination with organizations including ILO, the International Transport Workers' Federation and the International Chamber of Shipping established the Seafarer Crisis Action Team to monitor developments, coordinate efforts, communicate with stakeholders and provide focused support for seafarers in need of urgent assistance, especially in connection with crew changes, repatriation, medical access and abandonment (United Nations, 2020; and subsect. 5A, chap. 6). IMO reports that the Team has dealt with over 500 cases involving thousands of individual seafarers to date, and continues to respond to new cases (IMO, 2022).

5. Impacts on ocean sciences and observation

The impact of COVID-19 on global scientific production can be measured in different ways. According to Gao and others (2021), "researchers in the 'bench' sciences, female scientists, and those with young children experienced significant declines in research time and other publication-based metrics, according to data collected before the summer of 2020", and none of this is different in ocean sciences. Jiang and others (2022) pointed out that the amount of attention paid to the ocean during the pandemic was nearly negligible, despite its prominent effect on human well-being.

Due to the lockdown and movement restrictions, many fieldwork and research missions were temporarily suspended. This particularly impacted missions involving in situ data collection, such as expeditions and surveys on research vessels and laboratory experiments (Intergovernmental Oceanographic Commission of the United Nations Educational, Cultural and Scientific Organization (IOC-UNESCO), 2020). Several studies confirmed that, due to the cancellation of numerous research cruises and the disruption of ship-based observations, year-long gaps in time series data exist, which are irreversible and permanent (Boyer and others, 2023; Link and others, 2021). This disrupts records of trends and introduces a "dark" period that researchers cannot fill. For example, Viglione (2020) demonstrated how weather forecasts and climate records have COVID-19-associated gaps that cannot be filled. For some countries, data collection was not completely discontinued, but data quantity was reduced (Boyer and others, 2023; Erasmus and others, 2022). Boyer and others (2023) also demonstrated that ship days at sea for research by the National Oceanographic and Atmospheric Administration of the United States declined significantly in 2020 and the first quarter of 2021, reflecting the impacts of COVID-19 on ocean sciences and observation. Furthermore, work groups to discuss data were poorly attended, and certain consultations, such as environmental impact assessment consultations, were limited. Thus, reports and projects were mostly finalized with limited input from stakeholders (Link and others, 2021).

However, short-term ocean observations were not interrupted, nor were autonomous observations (Boyer and others, 2023). In addition, during the pandemic, research aimed at gaining a better understanding of the impacts of COVID-19 on maritime supply chains, port logistics and global maritime transportation was initiated (Boyer and others, 2023). Many researchers redirected their studies, often discontinuing their ongoing research. However, Visbeck (2020) stressed that, given the diversity

of research and areas related to ocean sciences, not all sectors of the ocean sciences community had the same level of access, abilities, choices and resilience.

International travel, which is essential for scientific collaboration and global research network meetings, was severely limited as a result of COVID-19. Innovative collaborations involving civil society and the private sector, which both hold significant potential for advancing real-time ocean observation and stewardship, were also severely limited (Enevoldsen and others, 2024). Conferences, workshops and joint expeditions were postponed, cancelled or held virtually, affecting collaborative projects between countries and institutions on maritime and ocean affairs.

The pandemic particularly impacted early-career researchers and early-career ocean professionals (Schadeberg and others, 2022). In terms of education and research, postgraduate courses and training programmes in maritime and ocean sciences were also affected. Doctoral and master's students who depended on data collection or participation in expeditions faced delays in completing their projects. This particularly affected applied research that required field research or face-to-face international cooperation.

In terms of funding, many governments and funding agencies redirected research resources to studies related to health and fighting the pandemic. As a result, other sciences, including ocean and maritime sciences, saw a drop in funding for projects not directly related to COVID-19. There was also a decrease in new grants and scholarships, as well as in funding for long-term projects and the reorientation of research (Schadeberg and others, 2022). This decline was impactful since States devote, on average, only 1.7% of their research budgets to ocean sciences (0.03% to 11.8%, depending on the country), much less than they spend on other major scientific fields (IOC-UNESCO, 2020).

Despite this, the coincidence between the COVID-19 pandemic, which began in 2020, and the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) offered a number of important links for ocean sciences (United Nations, 2024). Indeed, the pandemic brought to the forefront the need to think about global resilience and sustainability, themes that are also central to the Ocean Decade agenda.

In addition, awareness of the links between the ocean and public health, a central theme of the Ocean Decade, increased. Issues such as marine pollution, biodiversity loss and climate change, which all affect ocean health, came to be seen as essential to long-term human well-being. At the same time, virtual initiatives and virtual international collaboration were strengthened, creating new opportunities for inclusive global dialogue on the ocean. Virtual events allowed the participation of developing countries and scientists who might not have been able to attend face-to-face events. Virtual conferences also have the benefits of lower costs, time savings, increased flexibility and accessibility, and lower carbon emissions (Guetter and others, 2022). Lastly, many researchers were able to accurately predict the impacts of COVID-19 on scientific research, expertise that could be used to better cope with and prepare for future crises (Hobday and others, 2024).

6. Decrease in compliance and observation and associated increase in illegal activities

COVID-19 hampered the monitoring, controlling, surveilling and collection of fisheries data by fisheries observers (Erasmus and others, 2022). It was challenging to deploy fisheries observers, especially in view of concerns about their health and safety (Erasmus and others, 2022; Kearns, 2020). Some countries, such as Namibia, had a significant reduction in observed fishing trips in 2020 compared with 2019 and 2021 (Erasmus and others, 2022). Other countries, such as Canada, "pulled" fisheries observers from all vessels completely (Thomson, 2020). This reduction in observer coverage meant that some vessels had no observers and essentially no law enforcement or data collection. The absence of observers on board fishing vessels is a driver for illegal, unreported and unregulated (IUU) fishing activities (Erasmus and others, 2022). Monitoring of fishing activities must be maintained to ensure that control measures established by management are enforced and that IUU fishing activities do not increase. The most common impact on monitoring, control and surveillance activities reported was the disruption of at-sea observer programmes (FAO, 2021). Furthermore, because data collected by fisheries observers are used as inputs for stock assessment models, this disruption could have affected the evaluation of fish stocks.

The COVID-19 pandemic led to a reported rise in illegal activities relating to the fisheries sector and the protection

of the marine environment. A lack of monitoring and enforcement, and the increased needs of impoverished people, may have led to increased IUU fishing activities (Mallik and others, 2022).

In some regions, monitoring and enforcement mechanisms were severely impeded. For example, some regional fisheries management organizations (RFMOs) suspended observer coverage on board fishing vessels in areas they manage (Indian Ocean Tuna Commission Secretariat, 2020; Western and Central Pacific Fisheries Commission (WCPFC) Chair, 2020). At the domestic level, States took various measures, some of which positively impacted monitoring and enforcement procedures, while others impeded them.

Positive action taken included campaigns in Belize aimed at increasing awareness of laws and seeking the cooperation of the public in reporting IUU fishing activities (UNCTAD, 2022c). In Malaysia, border security was considered a priority, and an increase in coordination between enforcement authorities was noted (Phua and others, 2021). However, in other regions, monitoring and enforcement remained the same, but the negative impact of the pandemic on livelihoods led to increased infringement of fisheries laws. These illegal activities included fishing in no-take zones, the use of destructive fishing gear and even mangrove deforestation along coastlines (Phua and others, 2021).

In addition, a significant decrease in monitoring and enforcement efforts was also reported in several countries, often due to the reallocation of resources to other matters of national importance, such as public health and economic productivity. This led to an intensification of recreational and commercial fishing in some areas, with an increase in illegal fishing activities and cases of vessels fishing nearer to the coast (Bates and others, 2021; Bennett and others, 2020).

Also, wildlife conservation laws were not respected; for example, juvenile species in The Bahamas conch fisheries were illegally fished (Bates and others, 2021). Marine protected areas (MPAs) are usually afforded a higher level of legal protection, yet in some countries law enforcement became less of a priority, leading to an increase in illegal fishing in these areas (King and others, 2022; Phua and others, 2021). Automatic identification system data demonstrated that in the Chagos MPA the number of suspected illegal fishing vessels per month was 19 times higher in 2022 compared with the period from 2010 to 2020.

However, authorities could not board vessels due to COVID-19 restrictions, and this led to a reduction in convictions (Collins and others, 2023). Thus, an absence of fishing-related convictions during the pandemic may not equate to a reduction in offences, but could represent an absence of detection and enforcement. Likewise, the decrease in the quantity and accuracy of fisheries data during the pandemic due to reduced observer coverage and monitoring means that no complete picture of related illegal activities at sea exists. Trans-shipment by fishing vessels is regulated by States and RFMOs. However, trans-shipment records during the pandemic differed from those of previous years, and it was inferred that fishing companies might not have reported their activities "knowing of the poor monitoring of the activity at the time due to the pandemic" (Ministry of Fisheries and Trade of Tuvalu, 2023).

An increase in the disabling of automatic identification systems was also recorded during the pandemic, for example, on Spanish purse seiners and longliners in the Indian Ocean (Engel and Hobson, 2023). Under international law, automatic identification systems have important functions where their use is prescribed: they improve the safety and efficiency of navigation, enhance the safety of life at sea and protect the marine environment (IMO, 2015). Disabling automatic identification systems, which is illegal in cases where the system is prescribed, increases the risk of collisions, while also decreasing the transparency and effectiveness of monitoring and enforcement. However, automatic identification system laws are generally not enforced in the fisheries sector (Bunwaree, 2023).

Lastly, in terms of human rights and labour laws, fishing vessel crews were mistreated in some instances (Schwenzfeier and others, 2022).

7. Impact on trade and supply chains

The impacts of the COVID-19 pandemic on maritime trade – one of the most important sectors of the ocean economy – significantly affected the global economy (Liu and others, 2023; Xu and others, 2021). Due to the nature of the pandemic and the closure of national borders, the maritime industry was one of the most affected sectors

(Liu and others, 2023; Xu and others, 2021). However, the COVID-19 pandemic had contradictory impacts on maritime trade; it significantly reduced the global economy in the short term, while the export of many anti-epidemic materials also stimulated maritime trade growth.

From a regional perspective, the pandemic immediately impacted the Asia-Pacific region. The export routes of China were particularly hit, especially in the first quarter of 2020, when lockdowns affected production and supply chains. Nonetheless, this also affected shipping routes around the world. Container traffic in European ports was reduced due to the economic slowdown and mobility restrictions, with ship calls dropping by 10.2% (European Maritime Safety Agency (EMSA), 2024). Across the major ports in Europe, the countries most severely affected at the start of the pandemic, such as Italy and Spain, suffered from the restrictions imposed by the pandemic, with reduced traffic and port capacity, as well as disruptions to internal logistics. In the Americas, countries with a high dependence on imports and exports, such as Brazil and Mexico, suffered from delays and a reduced volume of transported goods. In the case of the United States, major ports such as Los Angeles and Long Beach faced congestion, due to high demand for imports following the recovery in trade. At the same time, they faced a shortage of port workers and containers.

In terms of the volume and profile of cargo handled, the reduction in global trade led to factory closures and quarantines, resulting in a significant drop in the volume of maritime cargo. From March to June 2020, when the most severe restrictions were in force, shipping activity was generally reduced (Millefiori and others, 2021). Mobility varied between −13.77% and −5.62% for container ships; −3.32% and +2.28% for dry bulk; −9.27% and −0.22% for wet bulk; and −42.77% and −19.57% for passenger traffic. In the second half of 2020, maritime trade began to recover as a consequence of an increase in demand for medical products and protective equipment, along with a leap in e-commerce – greatly altering the dynamics of the industry. The imbalance between demand and port capacity led to terminal congestion and delays in the delivery of goods. In general, nodes and links in the global shipping container network were severely damaged due to COVID-19 (Li and others, 2024).

The pandemic resulted in temporary port closures, reduced demand for energy and raw materials, and the unavailability of ships and containers (Khan and others, 2022). In response to the pressure on maritime transport, different kinds of emergency policies were enacted, with many countries adopting measures to guarantee the functioning of ports and essential cargo operations. In some cases, staffing regulations and port operations were temporarily relaxed to facilitate the movement of goods and maritime workers.

Some companies and countries began to re-evaluate their supply chains with a view to reducing their dependence on certain ports and routes. At the same time, the pandemic accelerated the adoption of digital technologies and automation in ports to improve efficiency and deal with future crises. It also impacted the consumption profile of certain segments of the population with online shopping and e-commerce. UNCTAD (2022a) sums up some elements that were crucial to navigating the COVID-19-related disruption to maritime transport and logistics, such as making use of international recommendations and directives, being prepared and having protocols, supporting workers, and facilitating and prioritizing the flow of essential goods (Villasante and others, 2021, 2024). For example, in fish markets, supermarkets and fishmongers, telephone and online sales progressively dominated, triggering home delivery, while direct sales also recovered over time during the pandemic. The retail sector made a great effort to promote online sales and home delivery to facilitate the consumption of fresh fish products (Villasante and others, 2021, 2024).

However, some studies also showed that COVID-19 generated new windows of opportunity for some countries and actors. For example, in the European Union, Carpenter and others (2023) found that the economic impact of COVID-19 on the fisheries sector was smaller than initially expected, and companies made a profit overall, despite some losses. This was in part due to low fuel prices, which reduced operating costs, and the early response from governments to support the sector. Nielsen and others (2023) combined surveys from industry representatives and official data to conclude that, on average, COVID-19 negatively impacted income. Overall, it seems clear that individual supply chains and firms, and possibly industries, experienced significant negative impacts of COVID-19, but that, in aggregate, this was mostly made up for by other supply chains and firms, which made the most of new opportunities (Nielsen and others, 2023). The fact that there were no or only moderate impacts on quantity and price for the sectors where data are available suggests that, in total, the aquaculture industry of the European Union and the markets it serves were highly resilient through the first stage of the pandemic (Nielsen and others, 2023).

8. Outlook

There has been an immense amount of interest and research related to the impacts of COVID-19 on the world's oceans (a Google Scholar search in October 2024 yielded over 160,000 results for the search terms "COVID-19" and "ocean"). However, the full scope of the pandemic's effects on the oceans and those who rely on them will never be fully known. Data gaps occurred during the pandemic, and some data sets (e.g. seafood worker demographics) were not collected regularly before, during or after the pandemic. In addition, further research is needed to determine whether some of the reported changes (e.g. in terms of biodiversity or species behaviour) were long-lasting or disappeared after the end of lockdown measures. These gaps and missed opportunities highlight the importance of continuing, and establishing more, long-term monitoring programmes, so that the effects of rare events can be captured, especially in underresourced locations. Importantly, more work is needed to assess the long-term effects of the pandemic and what lessons can be learned for future human pandemics and other extreme events for socioecological systems (White and Wulfing, 2024).

9. Key remaining knowledge gaps

There are insufficient long-term data on the effects of reduced human activity on marine ecosystems during the pandemic. In addition, it is unclear how shifts in consumer preferences for seafood, such as people cooking at home more, will affect the seafood industry in the long term. Furthermore, there are inadequate data on the ecological impacts of increased plastic waste, particularly single-use masks and personal protective equipment, on marine species and habitats. Comprehensive studies on how pandemic-related restrictions on scientific research expeditions affected the long-term monitoring of ocean systems are lacking. Also, the understanding of how pandemic-driven shifts in IUU fishing have impacted fish stocks and marine ecosystems is incomplete. Moreover, it is not known which effects of the COVID-19 pandemic were unique and which may inform future large-scale disruptions, such as other global pandemics. Lastly, the long-term impacts of reduced anthropogenic noise on marine species communication and behaviour are unclear.

10. Key remaining capacity-building gaps

Improved policies and protocols are needed to protect seafood workers, particularly those who work in crowded or moist working environments, from future pandemics. Increased knowledge of the demographics of those working in the seafood sector is also necessary. In addition, it is important to strengthen global monitoring and enforcement mechanisms in order to prevent an increase in illegal activities, such as IUU fishing, during crises that disrupt surveillance. Another area for improvement is the capacity for rapid adaptation in fisheries management, such as through the use of remote or automated monitoring systems, to mitigate gaps in observer programmes. Furthermore, developing sustainable, low-plastic personal protective equipment would reduce pollution in marine environments. Increased investment is needed in robust technologies and tools for autonomous ocean monitoring that could be used during disruptions to traditional research (White, 2025). Lastly, a greater focus on resilience planning in the seafood supply chain would help to prepare the industry for future pandemics by ensuring an equitable distribution of relief funds and the existence of safety protocols.

11. Conclusions

The COVID-19 pandemic profoundly impacted marine ecosystems, and those who rely on them, worldwide. The large amounts of plastics manufactured and used throughout the pandemic increased the illegal disposal of plastic waste into the oceans globally, causing plastic and microplastic pollution of the marine environment. However, the decrease in anthropogenic activity also altered the behaviour of marine species, for instance, leading to increased breeding and calling activity. Port operations were also severely impacted, slowing international trade

and commerce, while seafood workers were at particular risk of contracting the disease. There were also drops in the demand for seafood and tourism in coastal areas. Scientific research and fisheries observations were also hindered, leading to an increase in illegal fishing activities in some areas. As a result, it is critical to strengthen policies and address research gaps in order to handle future pandemics with more resiliency.

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Chapter 8
Indigenous, traditional owner and local community knowledge

Key points

- Indigenous, traditional owner and local community knowledge is increasingly being recognized as a valuable complement to knowledge systems and ocean governance models.
- Indigenous, traditional owner and local community knowledge has frequently been conceptualized by scientific and governance systems as only land-based, and there has been an assumption that it must be "integrated" or validated by non-Indigenous methodologies, which can lead to power imbalances and a loss of the cultural integrity of such knowledge.
- The effectiveness of knowledge systems can be constrained when they fail to recognize or engage with diverse world views, including Indigenous ways of knowing.
- Ocean governance models that incorporate Indigenous, traditional owner and local community knowledge are more likely to achieve comprehensive well-being outcomes, including by maintaining cultural and/or natural heritage, fostering community resilience and offering generational insight into marine ecosystems and their sustainable use.
- In order to achieve a sustainable future, it is necessary to take specific actions such as prioritizing Indigenous, traditional owner and local community knowledge leadership in decision-making, ensuring inclusive and equitable participation, aligning objectives, and legally recognizing and empowering such communities as equal stakeholders.
- Examples of mutually respectful and effective collaboration have been documented, where Indigenous, traditional owner and local community knowledge and scientific knowledge have been woven together to generate context-specific insights and more inclusive outcomes.
- In future World Ocean Assessments, the authors should aim to improve the inclusion of Indigenous, traditional owner and local community knowledge alongside conventional scientific knowledge and should seek to protect Indigenous, traditional and local values and rights.

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1. Introduction

Indigenous Peoples and traditional and local communities possess knowledge systems developed through generations of intimate interaction with their surrounding environment, often referred to as traditional ecological knowledge (Strand and others, 2024). These knowledge systems are based on lived experiences, cultural practices and long-term observations, and are transmitted across generations by means of oral traditions and cultural practices (Magni, 2017; Pictou, 2023). The methods of transmission, which involve stories, ceremonies and customary practices, are as important as the knowledge itself (Magni, 2017; Ogar and others, 2020). These knowledge systems are highly place-based and context-specific, and capture the complex relationships among people, species and ecosystems (Jessen and others, 2022; Strand and others, 2024).

In the present chapter, the terms "Indigenous Peoples" and "local communities", which are recognized by the United Nations, have been used, although it should be noted that other terms may be used in national contexts. In Australia, for instance, the term "traditional owner" specifically refers to Aboriginal and Torres Strait Islander peoples with cultural, spiritual or historical ties to particular areas of the land and sea (Davies and others, 2020).

It is important to emphasize that Indigenous, traditional owner and local community knowledge is a dynamic and evolving knowledge system that weaves Indigenous expertise with contemporary observations and lived experiences (Bay and others, 2023; Friedlander and Gaymer, 2021). It is deeply rooted in the relationship between Indigenous Peoples and traditional and local communities and their environments, and is a reflection of how communities engage with, manage and sustain natural resources while adapting in response to emerging challenges (Rist and others, 2019; Tilot and others, 2021). The adaptability of such knowledge makes it an essential tool for biodiversity conservation, environmental sustainability and marine resource management (Allison and others, 2023; Kitolelei and others, 2022; Ogar and others, 2020).

Recent publications by Strand and others (2024) and Allison and others (2023) highlight the growing and critical recognition of the role of Indigenous, traditional owner and local community knowledge in sustainable ocean management. Its role is being recognized in relation to several key areas, such as more inclusive and equitable ocean plans, the protection of marine biodiversity, ecosystem resilience and more holistic approaches to ocean governance that reflect the importance of socio-ecological systems (Barianaki and others, 2024; Frid and others, 2023; Ogar and others, 2020). This recognition is reflected in a recent publication by the Food and Agriculture Organization of the United Nations (FAO) on the governance of small-scale fisheries, which highlights how Indigenous knowledge systems contribute not only to environmental sustainability, but also to inclusive management and knowledge-sharing within socioecological systems (Berkes and Franz, 2025). This holistic approach often incorporates spiritual and cultural values and has an emphasis on the interconnectedness of people and the sea (Rist and others, 2019; Tilot and others, 2021). Governance structures that include Indigenous, traditional owner and local community knowledge are more likely to result in multifaceted well-being (Allison and others, 2023; Magni, 2017), because they are based on the interconnectedness of social, economic, environmental and cultural aspects of life, prioritize community interests, promote sustainable practices, preserve cultural identity, and demonstrate adaptability in the face of changing circumstances.

As the world faces multiple environmental crises, there is growing recognition that Indigenous, traditional owner and local community knowledge can provide insights for sustainable resource management and biodiversity conservation. This has led to the incorporation of such knowledge into global processes and assessments, such as the Global Assessment Report on Biodiversity and Ecosystem Services (Balvanera and others, 2022; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019), reports by the Intergovernmental Panel on Climate Change (IPCC) (Ford and others, 2016) and contributions to the Convention on Biological Diversity (Parks and Tsioumani, 2023). Similarly, there has been recognition of the need to meaningfully include and engage with Indigenous, traditional owner and local community knowledge throughout the *World Ocean Assessment* process, which was established by the General Assembly in 2004 and is currently in its third cycle, in order to capture a more holistic understanding of the state of the marine environment and inform sustainable ocean governance. Moreover, recent global initiatives, such as the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and the Agreement under the United Nations Convention on the Law of the Sea on the

Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction, explicitly recognize the importance of Indigenous, traditional owner and local community knowledge in promoting ocean sustainability (Intergovernmental Oceanic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO-IOC), 2021; United Nations, 2023). These frameworks contain an emphasis on the need for knowledge-sharing and culturally appropriate, equal participation, principles that are aligned with the United Nations Declaration on the Rights of Indigenous Peoples.

The first *World Ocean Assessment* cycle, conducted over the period 2010–2014, was focused on producing the first global integrative marine assessment (Division for Ocean Affairs and the Law of the Sea (UNDOALOS), 2017). However, the *Assessment* did not explicitly incorporate Indigenous, traditional owner and local community knowledge. In the lead-up to the second cycle, which began in 2016, an assessment was carried out to identify gaps in the first cycle of the *World Ocean Assessment*, which included the lack of representation of diverse knowledge systems, such as Indigenous, traditional owner and local community knowledge. Based on this, technical abstracts were produced for the second cycle that could better summarize information for policymakers. However, the inclusion of Indigenous, traditional owner and local community knowledge in the second *World Ocean Assessment* was still limited. It was only in the scoping and planning for the third cycle, starting in 2021, that the explicit recognition of such knowledge emerged as a priority. The shift towards greater inclusion was driven by feedback from regional workshops on the *Assessment*, in which participants flagged the lack of inclusion of Indigenous, traditional owner and local community knowledge as a major gap and highlighted the need to acknowledge and incorporate it in the assessment process.

As a result, a dedicated chapter on Indigenous, traditional owner and local community knowledge was included in the outline for the third *World Ocean Assessment*. Focused regional workshops were held and case studies were solicited from stakeholders with the goal of documenting diverse experiences and insights in the present chapter. While this represents progress, more work is needed to ensure that such knowledge is more fully included in future World Ocean Assessments and in related global and regional ocean assessment processes. The participants in regional workshops, including the representatives of Indigenous, traditional owner and local community knowledge, see the present chapter as an important first step towards establishing a stronger partnership between such knowledge holders and the conventional scientific community in assessing the state of the world's oceans. They emphasized the need to go beyond tokenistic inclusion and truly weave their knowledge into the *World Ocean Assessment* process and outputs as an equal and essential contribution.

2. Acknowledging the value and application of Indigenous knowledge

Many ancient Indigenous creation or origin stories from around the world centre on life beginning with or in relation to the ocean, the sea or water more generally. Centuries-old archaeological shell midden sites (Rick, 2024) and petroglyphs, including of whales or whale hunting, exist across the globe, revealing Indigenous knowledge, knowledge transformations and human relationships with both land and water (Charette and others, 2021). According to the Ocean and Human Rights Platform, there are 27 million Indigenous people, in nearly 2,000 communities across 87 countries, living in coastal areas (Fears, 2016). There are also sea-nomadic or mobile Indigenous societies, such as the Bajau and Moken peoples of South-East Asia, whose deep maritime knowledge and mobility are central to their identities and ways of life. These communities, often referred to as "sea peoples", maintain rich traditions of marine stewardship, including sustainable fishing, freediving and ocean navigation (Boni and others, 2024). However, countless Indigenous Peoples are increasingly being displaced, and torn from their ancestral oceanic sources of food and livelihood (Crosman and others, 2022). Knowing that their "lives, food, and livelihoods depend on the health of ocean resources, Indigenous Peoples have, through millennia, developed social-ecological systems of marine resources management that rely on cultural traditions as well as an intimate, dynamic and long-term knowledge of the environment" (Vierros and others, 2020).

The importance of Indigenous, traditional owner and local community knowledge for protecting and conserving biodiversity and addressing climate change is increasingly being recognized by international forums such as the Conference of the Parties to the Convention on Biological Diversity, the International Union for Conservation of Nature (IUCN), the Permanent Forum on Indigenous Issues and IPBES. Recently, the importance

of Indigenous knowledge for ocean sustainability was highlighted in a series of "blue papers" commissioned by the High-level Panel for a Sustainable Ocean Economy, which call for the "co-production" of ocean plans with Indigenous Peoples (Strand and others, 2024). Many challenges remain. In practice, in international decision-making spheres, it is difficult to apply the United Nations Declaration on the Rights of Indigenous Peoples and the new Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, and to ensure respect for fundamental human rights. This is partly because ocean governance is spread across multiple overlapping legal frameworks and institutions (Bodansky, 2024; Vierros and others, 2020), which makes it hard to consistently recognize and uphold Indigenous, traditional owner and local community knowledge and rights in processes related to deep-sea mining (Morgera, 2024) and with a view to achieving Sustainable Development Goal 14 on life below water (Haas, 2023).

A major barrier lies in the fact that, under non-Indigenous knowledge-based, conventional scientific and governance systems, the ocean is often treated as being separate from the land; Indigenous Peoples are conceived of as being only land-based; and there is an assumption that Indigenous knowledge needs to be "integrated" or validated by non-Indigenous knowledge or conventional scientific methodologies (Crosman and others, 2022; Jones and others, 2024; Strand and others, 2024). As stated by Enyew and others (2021):

> This land-sea dichotomy contravenes the holistic vision of Indigenous peoples, and ignores the fact that activities conducted on land may affect the rights of local communities and Indigenous [P]eoples related to their traditional use of marine spaces and resources. … The law of the sea also principally follows a zonal division of the ocean space, where each maritime zone is subject to different levels of State sovereignty and jurisdiction, and governed by distinct regulatory mechanisms. This zonal approach and the associated logic of State sovereignty has various consequences on Indigenous peoples.

For some Indigenous Peoples, it is not only land and water that are connected, but all life forms. This interconnectedness is reflected in principles of mutual reciprocity that guide relationships between people, land, water and other beings, shaping practices related to food and livelihoods. These principles aim to sustain both ecosystem and human communities across generations (Crosman and others, 2022; Enyew and others, 2021; Pictou, 2023; Somiah, 2022; Von Der Porten and others, 2019). Many Indigenous Peoples assert that the concepts of life, energy and spirituality are synonymous. All are intertwined and embedded in the territory and, therefore, cannot be addressed separately. At the core of existence, there is no division between water, plants, animals and even human beings. For that reason, life, spirituality, water and territory cannot be discussed in isolation (Martinez-Cruz and others, 2024).

It is also important to note that Indigenous relational worldviews and practices derive from a vast array of diverse global contexts and are not static or frozen in time or space. Indigenous Peoples can also be mobile and transitionary between and across various scales of diverse lands and waters formulating local, national and international diplomacies and protocols (Ambers and George, 2024; Borrows, 2016; Crosman and others, 2022).

These concepts of harmonization and fluid internationalism are synonymous with "Two-Eyed Seeing", which applies the strengths of both Indigenous and non-Indigenous worldviews (Marshall and others, 2021) or embraces multiple knowledge systems and "diverse ways of knowing" (Strand and others, 2024), without discrediting the diversity of approaches.

3. Approaches and guiding principles for applying Indigenous, traditional owner and local community knowledge

Approaches and guiding principles for working with Indigenous, traditional owner and local community knowledge are less well documented than the challenges of working with it. However, there is increasing recognition of the value and role of Indigenous Peoples and local knowledge, and of the need for knowledge co-creation to enhance ocean governance (Strand and others, 2022).

Emerging frameworks include co-production approaches grounded in Indigenous research protocols and priorities, such as those developed in Arctic research (Yua and others, 2022) and in diverse community contexts (Rathwell and others, 2025). It is also important to note that many Indigenous Nations have local protocols and knowledge-sharing principles that may not

be publicly available. This growing field is reflected in partnership models that bring together disparate worldviews (Indigenous and non-Indigenous) in cross-cultural collaboration to challenge the status quo, such as ethical space of engagement (Ermine, 2007) and knowledge co-creation as Two-Eyed Seeing (Bartlett and others, 2012; Marshall and others, 2021; Reid and others, 2021).

Understanding Indigenous, traditional owner and local community involves understanding that Indigenous Peoples do not all share the same worldviews. However, their worldviews do share common values inherent to Indigenous Peoples. Key values include relatedness, respect and reciprocity as a "package" that underpins the Indigenous way of life. Relatedness, a connection to the physical and spiritual realms, also referred to as kinship, is maintained through respectful relationships with other people and species that are reinforced by cultural practices. Reciprocity is required to maintain respectful relationships. As stewards, people have a responsibility to maintain balance and harmony with the natural and spiritual realms (Artelle and others, 2018; McMillan and Prosper, 2016; Whyte, 2013).

Even when differences between Indigenous and non-Indigenous knowledge systems are recognized, working within the context of Indigenous, traditional owner and local community knowledge poses several challenges, especially when knowledge holders and those engaging with such knowledge lack awareness of these distinctions or lack training in inter- and transdisciplinary approaches to working across knowledge systems (Fernández-Llamazares and others, 2021; Ens and others, 2012). Some scholars have even cautioned against "integrating" such knowledge because it implies the prioritization of non-Indigenous ways of knowing, a failure to consider Indigenous values and worldviews, and the lack of a shared understanding of such knowledge as well as of the benefit of knowledge pluralism, which is valued and used by Indigenous Peoples (Bingham and others, 2021; Latulippe, 2015).

Despite these barriers, Indigenous and non-Indigenous knowledge and understanding have been successfully bridged (Alexander and others, 2019), with for example the integration of qualitative data derived from social science methods in quantitative models (Ban and others, 2017; Lam and others, 2019), as well as the use of Bayesian Belief Networks, in which qualitative and quantitative indicators developed through participatory workshops are incorporated into a structured modelling framework to bridge Indigenous and scientific knowledge, such as in Slave River Delta, Canada (Lam and others, 2019). In this regard, in "The assessment report on the diverse values and valuation of nature" (Termansen and others, 2022), IPBES draws attention to practices that are consistent with the values of Indigenous and local communities. It stresses the importance of recognizing plural values of nature – relational, spiritual and cultural – and expresses support for valuation processes that are co-developed, context-specific and respectful of knowledge sovereignty.

Similarly, qualitative data derived from interviews with Indigenous fishers who estimated catch rates for a culturally important species based on past experiences were used to parameterize simulations to assess declines in catch rates (Ban and others, 2017). Another recent study by Gryba and others (2025) demonstrates the use of Indigenous, traditional owner and local community knowledge as a sole data source in the development of habitat selection models, thus reinforcing the value of such knowledge in quantitative ecological research. These examples show that it is possible to use Indigenous knowledge acquired through social science methods in quantitative-based modelling.

4. Scoping work for the third *World Ocean Assessment*: regional workshops and case study

The Division for Ocean Affairs and the Law of the Sea of the United Nations Secretariat held a series of regional workshops and examined one case study in an effort to understand the scope of Indigenous, traditional owner and local community knowledge and the global range of issues related to it, with a view to better incorporating such knowledge into the third *World Ocean Assessment*.

Regional workshops

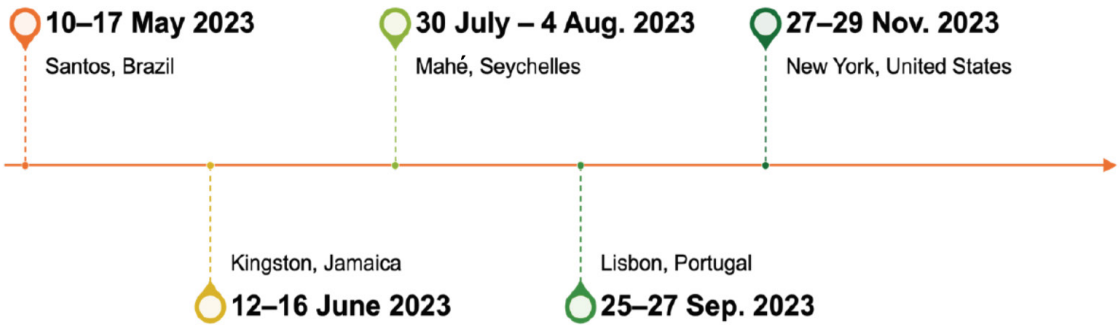
Regional workshops were held in Brazil, Jamaica, Portugal, Seychelles and the United States of America. Each workshop brought together representatives of Indigenous Peoples, traditional owners and local communities, as well as experts and practitioners from ocean-related

institutions (see figure I). The scoping process was focused on identifying regional needs, reviewing existing information and considering what should be included in the assessment to make it as useful as possible for policymakers.

To allow for comparison across regions, workshop deliberations were centred on five key questions:

1. How might Indigenous, traditional owner and local community knowledge assist in gaining an understanding of the economic and social drivers that are producing the changes observed in the ocean?
2. What are the current consequences of ongoing changes in the ocean for Indigenous, traditional owner and local community social systems and cultural security?
3. What do future projections and outlooks for the ocean look like across societal and cultural groups and Indigenous Peoples?
4. How can a sustainable future be achieved in a way that will give all components of society, including Indigenous Peoples, traditional owners and local communities, an equal role?
5. Which socioeconomic factors will have the greatest influence on the contributions that societal and cultural groups, including Indigenous Peoples, traditional owners and local communities, can make to achieving a sustainable future?

Figure I
Timeline of regional workshops



Source: Prepared by the writing team.

In order to help to summarize the regional contributions, workshop notes were analysed using a grounded theory approach. The participants' responses were coded across the five main questions and common themes and keywords were identified. The terms that appeared most frequently in all workshop texts were used to generate a word cloud (see figure II). The figure highlights the most common concepts that arose in the discussions of Indigenous, traditional owner and local community knowledge in relation to ocean governance, cultural heritage and community resilience.

The word cloud (figure II) is not intended to be conclusive or to capture the full diversity of Indigenous, traditional owner and local community knowledge, but rather to summarize key views and ideas that were raised in the regional workshops – especially those of traditional and local communities and ocean-related experts. As such, it provides a broad overview of the views shared by the participants in the regional workshops. The most common terms – "knowledge", "traditional", "Indigenous", "local", "communities", "groups" and "impacts" – reflect the central role of culturally rooted, place-based knowledge systems in interpreting ocean change and contributing to equitable governance.

The repeated occurrence of terms such as "understanding", "change", "social", "process" and "sustainable" underlines the dynamic and interdisciplinary nature of Indigenous, traditional owner and local community in relation to both environmental and social change. Words like "recognition", "culture", "rights", "governance", "access" and "inclusion" all speak to participants' calls for greater respect for the holders of that knowledge as equal partners in ocean governance processes. Insights from regional workshops reveal the vital role that such knowledge plays in supporting ocean governance, maintaining cultural heritage and fostering community resilience, particularly in light of the ongoing changes in the ocean (see figure III).

Figure II

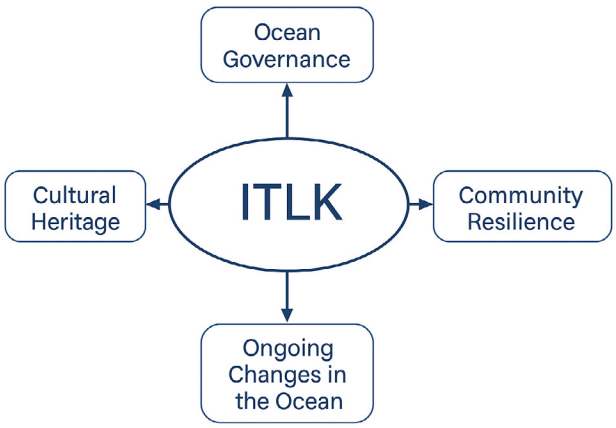
Word cloud highlighting the most frequently mentioned concepts in response to questions posed at regional workshops



Source: Prepared by the writing team.

Figure III

Conceptual diagram illustrating key relationships, derived from regional workshop responses, showing how Indigenous, traditional owner and local community knowledge (ITLK) contributes to ocean governance, cultural heritage and community resilience in the context of ongoing ocean change



Source: Prepared by the writing team.

Given its long-standing historical use and the years invested in protecting and passing it down from one generation to the next, Indigenous, traditional owner and local community knowledge provides valuable, culturally authoritative and context-specific insights for managing coastal and marine resources. It offers a lens for understanding the economic and social drivers behind current changes in the ocean. In addition, Indigenous communities have a wealth of knowledge about ocean-related changes that can be used to calibrate scientific forecasts (Kaiser and others, 2019). Indigenous Peoples are aware of how to define, understand and use natural resources in a sustainable manner. They are also key players, and their different perspective can help to better understand the crises and challenges and how to overcome them.

Many Indigenous Peoples possess valuable knowledge that contributes to the management of coastal resources and to the systems and practices through which those resources are accessed, harvested and governed. Therefore, the effects of ongoing ocean change on those communities cannot be fully understood without incorporating an Indigenous, traditional owner and local community knowledge perspective. This is because the impacts of ocean changes extend beyond the biological realm – they disrupt Indigenous Peoples' ways of life, including their social systems, erode their cultural identity, and exacerbate their vulnerability to environmental and economic pressures. For instance, the loss of a biological species is not only a significant ecological loss; it can also contribute to the loss of cultural identity.

This loss of cultural identity is exemplified by the experiences of Indigenous and local communities. As one participant noted, "climate change impacts fish stocks, affecting local activities and cultural heritage". The decline of key species not only disrupts livelihoods, but also causes the loss of traditional knowledge and cultural identity. In addition, "threats to sacred sites and cultural traditions", which was mentioned by a participant, reflects the fact that environmental degradation can lead to a loss of species and spaces that are critical to communities' identities. Despite those impacts, the loss of traditional knowledge and cultural identity is often overlooked in scientific assessments. There is a need for more comprehensive scientific frameworks that address not only ecological changes, but also their cultural and spiritual impacts.

The cultural assets of most Indigenous Peoples, traditional owners and local communities are closely tied to the natural environment. Therefore, significant changes in the environment can undermine the cultural security of the holders of Indigenous, traditional owner and local community knowledge. This close connection makes

them especially vulnerable to both environmental and economic changes. Climate change-induced displacement, loss of livelihoods, and food and water scarcity were among the most prevalent issues that emerged from the discussions. Economic changes, such as growth in blue economies, increase the probability of climate injustice, exacerbating marginalization and further weakening societal coping mechanisms. Adaptive strategies, informed planning and inclusivity in governance and decision-making processes are required to address these vulnerabilities. As one participant noted, "inclusive and equitable participation in decision-making processes" is essential for ensuring that the voices of Indigenous and local communities are heard. Examples include co-management frameworks and community-based fisheries management, which provide platforms for equitable participation.

Future projections and outlooks are different across societal and cultural groups, and are very different for Indigenous and non-Indigenous communities due to their different worldviews, ways of knowing and knowledge systems. There will be regional variations in the effects of climate change, such as temperature changes and sea-level rise, so communities and groups with different socioeconomic status will be affected differently. Unfortunately, if the world continues with "business as usual", the outlook will only become bleaker and inequality will inevitably increase, with varying effects for different groups depending on the state of the economy and groups' access to the ocean and its resources.

The cost of living will be higher in the future for Indigenous Peoples, who have limited access to alternative sources of income and to technology, and they will be forced to transform their lives (e.g. move to higher ground or find new, less ocean-dependent livelihoods). Therefore, assessments of climate change impacts and adaptation strategies should take into account diverse perspectives in order to truly reflect realities on the ground.

In order to ensure that assessments are balanced, it is necessary to take targeted actions that position all components of society, including Indigenous Peoples, traditional owners and local communities, as equal stakeholders. Such actions include promoting Indigenous leadership in decision-making roles and embedding inclusive and equitable participation in decision-making processes. It is essential to align government objectives with Indigenous communities' goals, while enforcing policies that protect their rights. It is vital to strengthen partnerships, including for capacity-building, and to develop bottom-up governance approaches that prioritize local agency. In addition, incorporating traditional knowledge into formal systems through transdisciplinary approaches and integrating it into environmental impact assessments ensures that these communities' contributions are recognized and valued. Ultimately, Indigenous Peoples, traditional owners and local communities are the ones with the best interests of their localities at heart, whether developmental or otherwise, and therefore what they think and say about their local areas matters. Indigenous Peoples hold internationally recognized cultural and legal rights, which are not always fully respected in practice.

The socioeconomic factors that will have the greatest impact on social and cultural groups' chances of achieving a sustainable future include recognition, empowerment and inclusive governance. Legal recognition that empowers these communities is a starting point, as it will ensure that their rights and territories are respected and included in broader governance frameworks. Embedding inclusive, deliberative advisory processes in marine resource management systems promotes equal participation and collaboration. In addition, promoting Indigenous Peoples, traditional owners and local communities in leadership positions improves their ability to influence decision-making processes. Aligning government objectives with those of these communities, such as by balancing Governments' need to create employment with ecosystem capacity, ensures that policies are both sustainable and equitable. Ensuring that these groups participate in rules- and decision-making processes at multiple levels and securing communities' tenure rights strengthen their capacity to contribute effectively. Lastly, advancing social justice, equality and equity across groups is essential to addressing historical inequalities and building a future where all communities can thrive and where no one is left behind.

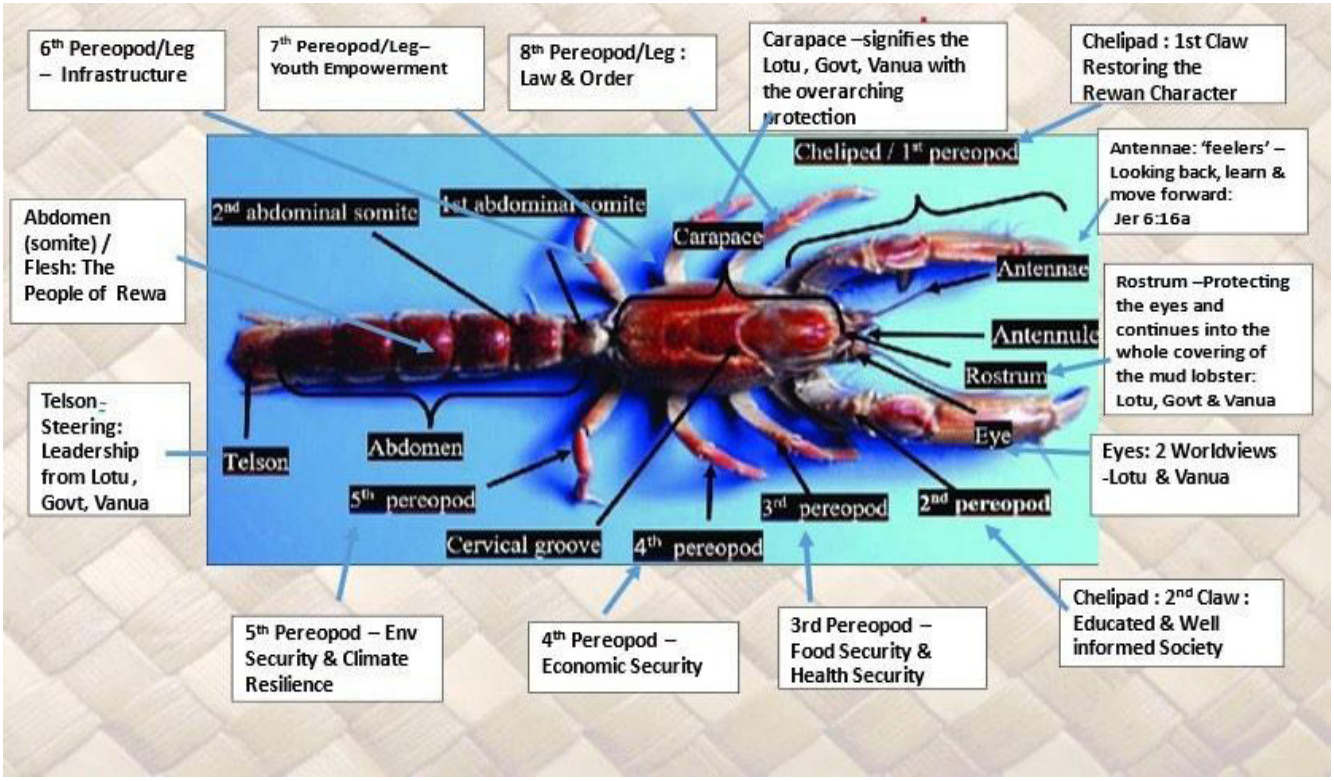
Case study: Indigenous methodologies and frameworks of Fiji – *mana* (mud lobster)

Indigenous society in Fiji, and its kinship system, uses sayings and idioms for teaching and instructions. There is a deep sense of interconnectedness in the Indigenous world, and in Fiji, every Indigenous person has a totemic plant and animal (a fish, bird or terrestrial animal). Garibaldi and Turner (2004) define "cultural keystone species", or totems, as the "culturally salient species that shape in a major way the cultural identity of a people, as reflected in the fundamental roles these species have in diet, materials, medicine, and/or spiritual practices". Interconnectedness in the Fijian world is represented by

totemism. As expressed by Tuwere (2002), "the totems represent among other things the interdependence of land, sea or river, and sky in the world of Fijians. They are usually a trilogy of linked ika (fish); kau (trees); and manumanu (bird, animal or insect)". These totems (such as the mud lobster, or *mana* in Fijian) can be used metaphorically to represent a framework for community planning or even academic writing, such as a thesis or a methodology. The Kakala research framework by Professor Konai Thaman (Johansson-Fua, 2023; Thaman, 1997) is an example of a Pacific method of teaching and learning. It was intended to encourage Pacific students to articulate theories from their perspectives and to recognize Pacific worldviews in their thinking and learning (Thaman, 1997).

When collaborating with Indigenous Peoples and local communities, it is good practice to communicate in the local language and translate any printed material into the local language.

Figure IV
Framework of the Rewa Strategic Development Plan, employing the *mana* (mud lobster)



Source: Rewa Strategic Development Plan 2025–2028.

Note: This framework is illustrative of Indigenous methodologies and frameworks that weave cultural values and ecological understanding into sustainable development strategies.

In the Rewa Strategic Development Plan of Fiji, the mud lobster (*Thalassina anomala*) is used as a metaphor for the Plan's framework – in terms of the physiology and essence of the *mana* (see figure IV). For instance, in terms of physiology, the eight legs (pereopods) of the mud lobster represent the eight priority areas of the Plan, while, in terms of "essence", mud lobsters are recognized for their ecological role as "friends of the mangroves", as their burrowing is important for the recycling of nutrients in the mangrove ecosystem. This resonates with the Indigenous People of Rewa, who live in the Rewa Delta, surrounded by mangroves. This metaphor illustrates how the Plan integrates cultural values and ecological understanding to promote sustainable development. The use of the *mana* also contextualizes the Plan, increases its relevance and a sense of ownership by Indigenous users and audiences, and helps to minimize ideas getting "lost in translation" as a result of the imposition of foreign or "outside" concepts and values. It also helps to rekindle a sense of identity and to revive Indigenous, traditional owner and local community knowledge.

5. Conclusion and outlook

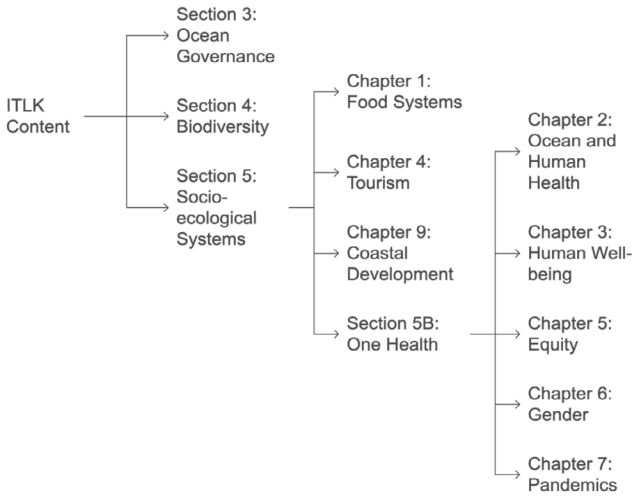
Indigenous, traditional owner and local community knowledge systems represent unique worldviews, epistemologies and ways of understanding the environment. Although such knowledge is increasingly recognized globally, many attempts to integrate it into non-Indigenous or scientific frameworks often result in power imbalances because the knowledge is treated as data to be integrated into existing management structures, rather than as a knowledge system in its own right. This approach can undermine the integrity and autonomy of these knowledge systems to the point where Indigenous, traditional owner and local community knowledge loses its cultural context and becomes oversimplified to fit existing narratives (Shackeroff and Campbell, 2007).

In the context of the *World Ocean Assessment*, it is suggested that, in the current process and in future assessments, Indigenous, traditional owner and local community knowledge should be better incorporated and respected, alongside non-traditional knowledge. This follows the global trend of the growing recognition of, and engagement with, such knowledge to support better environmental and social management outcomes. The *World Ocean Assessment* should cover diverse issues faced by Indigenous Peoples in different regions.

There are many sections and chapters of the *World Ocean Assessment* in which Indigenous, traditional owner and local community knowledge overlaps with current content and/or where such content may be included in future *World Ocean Assessment* cycles, as reflected in figure V. Incorporating it in these sections would help to ensure that future World Ocean Assessments truly champion Indigenous, traditional owner and local community as an essential contributor to sustainable ocean management, thereby fostering more inclusive and effective environmental stewardship.

Figure V

Sections and chapters of the *World Ocean Assessment* where Indigenous, traditional owner and local community knowledge overlaps with current content or may be included in future cycles



Source: Prepared by the writing team.

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